

Final Report

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Acronyms

ARB-Air Resource Board
AQMD-Air Quality Management District
Btu/h-British Thermal Unit per Hour
CB-Cleaver Brooks Company
CO-Carbon Monoxide
CO₂-Carbon Dioxide
CPC-Clement Pappas & Company
DAQ-Data Acquisition
FAR-Fuel-Air Ratio
FDA-Field Demonstration Agreement
GTI-Gas Technology Institute
HAH-Humidifying Air Heater
HHV-Higher Heating Value
HP-Horse Power, Boiler
HPE-High Pressure Economizer
HRS-Heat Recovery System
ICAT- Innovative Clean Air Technologies
ICS-Integrated Control System
LPE-Low Pressure Economizer
NO_x-Sum of Oxides of Nitrogen
O₂-Oxygen
ppmv-Parts per Million on Volume Basis
RFM-R.F. MacDonald Company
scfh-Standard Cubic Feet per Hour
THC-Total Hydrocarbons
TMC-Transport Membrane Condenser
VOC-Volatile Organic Compound
UL-Underwriters Laboratories, Inc.

Executive Summary

GTI and Cleaver-Brooks have developed a new gas-fired steam generation system—the Super Boiler—for increased energy efficiency, reduced equipment size, and reduced emissions. The system consists of a firetube boiler with a unique staged furnace design, a two-stage burner system with engineered internal recirculation and interstage cooling integral to the boiler, unique convective pass design with extended internal surfaces for enhanced heat transfer, and a novel integrated heat recovery system to extract maximum energy from the flue gas. With these combined innovations, the Super Boiler technical goals were set at 94% HHV fuel efficiency, operation on natural gas with <5 ppmv NO_x, <5 ppmv VOC, <30 ppm CO (ref 3%O₂), and 50% smaller than conventional boilers of similar steam output. To demonstrate these technical goals, the stated objectives of the project were to select a host site, fabricate and install the Super Boiler, evaluate system performance, and perform a SCAQMD market analysis. The industrial demonstration site selected was Clement Pappas located in Ontario, California and the boiler output was determined to be 300 HP.

The Super Boiler combustion system is based on two stage combustion which combines air staging, internal flue gas recirculation, interstage cooling, and unique fuel-air mixing technology to achieve low emissions rather than external flue gas recirculation which is most commonly used today. Two stage combustion provides lower emissions because of the integrated design of the boiler and combustion system which permit precise control of peak flame temperatures in both primary and secondary stages of combustion. Single stage combustion systems used today have limitations because they try to control the peak flame temperatures in one stage using external flue gas and hence flame temperatures often exceed 2800°F at which point thermal NO_x formation occurs, hence these single stage burners are typically limited to 9 ppmv NO_x. Addition of larger amounts of flue gas recirculation in single stage burners makes combustion unstable. Finally single stage burners require higher excess air levels throughout the firing range to provide stability.

To reduce equipment size, the Super Boiler's dual furnace design increases radiant heat transfer to the furnace walls, allowing shorter overall furnace length, and also employs convective tubes with extended surfaces that increase heat transfer by up to 18-fold compared to conventional bare tubes. In this way, a two-pass boiler can achieve the same efficiency as a traditional three or four-pass firetube boiler design. The Super Boiler is consequently up to 50% smaller in footprint, has a smaller diameter, and is up to 50% lower in weight, resulting in very compact design with reduced material cost and labor costs, while requiring less boiler room floor space.

For enhanced energy efficiency, the heat recovery system (HRS) uses a transport membrane condenser (TMC), a humidifying air heater (HAH), and a split-stage economizer to extract maximum energy from the flue gas. The TMC is a new innovation that pulls a major portion of water vapor produced by the combustion process from the flue gas along with its sensible and latent heat. This results in nearly 100% transfer of heat to the boiler feed water. The HAH improves the effectiveness of the TMC, particularly in steam systems that do not have a large amount of cold makeup water which maximizes heat transfer in the TMC. In addition, the HAH also humidifies the combustion air to reduce NO_x formation. The split-stage economizer preheats boiler feed water in the same way as a conventional economizer, but extracts more heat by working in tandem with the TMC and HAH to reduce flue gas temperature. These components are designed to work synergistically to achieve energy efficiencies of 92-94% which is 10 to 12% higher than today's typical firetube boilers.

The performance tests were divided into a short term parametric tests and long term performance tests. The parametric tests quantified efficiency and emissions based on variables

such as primary stage stoichiometry, stack excess oxygen levels, ramp up and ramp down performance, and influence of the HAH. Each point for the parametric tests was collected near steady state conditions. The long term testing simply was collection of data during the boiler cycling while carrying the plant's process load and this data provides emissions and efficiency over time, without constant attention from GTI or the plant personnel. Emissions for the parametric tests were measured with a Horiba analyzer that was certified by a relative accuracy test audit performed by a URS Corporation. Emissions for the long term testing was done with an Ecom A+ analyzer with electrochemical cells calibrated twice a month.

The parametric tests were performed in February and March of 2008. For all the parametric tests NO_x and CO emissions, both corrected to 3% O₂, ranged from 3.4 to 7.2 ppmv and 2.4 to 60 ppmv, respectively. It should be noted that these ranges are for all the tests with the different parametric test variables described above. Thermal efficiency from the parametric tests demonstrated the Super Boiler system logged a steady-state mean thermodynamic efficiency¹ of 92.1%. Fuel-to-steam² conversion ranged from 89.7 to 99.3% with a mean of 97.0%, depending primarily on the amount of returned condensate and to a minor extent on the firing rate.

The long term testing did not start until February 18, 2009 due to problems with permitting and plant processing problems. The long term testing will continue for the remaining 6 months until the middle of August, 2009. Values for the parametric testing emissions and the long term testing (to date) are comparable even though there was a year between the tests. Hence it is predicted that there will be little to no change in the range of data collected by the end of the 6 month period. It should also be noted that VOC emissions were not available and therefore CO emission data was taken as an indicator of VOC emissions (CO and VOC emissions typically track closely for burners firing natural gas).

The emissions data collected February 26 and 27 during normal operation without startups and shut downs for NO_x and CO emissions, both corrected to 3% O₂, ranged from 1.5 to 7.9 ppmv and 5 to >190 ppmv, respectively. The average for this range of NO_x and CO was 4.0 ppmv and 21 ppmv, respectively. There were spikes of NO_x during startup that went as high as 11 ppmv on one occasion while spikes in CO went above the range of the analyzer to 200 ppmv on several occasions (hence a true CO maximum average is not possible, but it would be at least 191 ppmv).

The methods used to calculate efficiency for the long term testing were the fuel to steam² and combustion³ methods. The combustion efficiency varied between 91.8 to 94.8% with an average of 93.0%. Data plots shown in the body of this report show fluctuations in the efficiencies. These fluctuations can be partially explained by the variation in the transport of flue gas moisture through the membrane and the response time of the flue gas thermocouples. The fuel to steam efficiency was less useful because it was not done at steady conditions so the values varied significantly due to the lag in response time of the natural gas flow rate to the steam flow rate. These values varied from 40.9 to 100% with an average of 90.8%.

¹ Thermodynamic efficiency is defined as $(Q_{\text{steam}})/(Q_{\text{fuel}}+Q_{\text{make-up water}}+Q_{\text{air}}+Q_{\text{condensate}}+Q_{\text{return}})\times 100$ where Q represents the heat values for the different components.

² Fuel-to-steam conversion is defined as $(Q_{\text{steam}})/(Q_{\text{fuel}})\times 100$ where Q represents the heat values for the different components.

³ Combustion Efficiency based on Stack Losses is defined as $100-L_{\text{fluegas}}+L_{\text{TMC}}$ where L represents the heat loss values.

The **averages** for NO_x and CO for both the parametric tests and the long term testing met the goal of 5 ppmv and 30 ppmv, respectively, even though there were some short term conditions where the goals were exceeded. The actual 93.0% efficiency was close to the goal of 94% HHV and the goal could have been achieved if the host site had used higher amounts of makeup water. Finally it should be noted that the parametric test data collected under steady state conditions is somewhat biased because the produced steam was vented during these test and therefore makeup water usage was higher than normal, making the TMC more efficient when compared to normal unvented operation.

The Super Boiler can benefit California South Coast AQMD region in the areas of fuel savings, fuel cost, lower emissions, and water savings. These benefits are discussed at length in the body of the report but here is a brief summary.

- Based on current estimated fuel-to-steam efficiency of 80% for existing boilers, replacement with Super Boilers would ultimately save 13% of natural gas, or 2.5 TBtu annually.
- With an average California price of \$6 per million Btu, the annual dollar savings from replacement with Super Boilers would equate to \$15.0 million in natural gas costs.
- The resulting reduction would be 49 tons of NO_x and 515 tons of CO. These reductions are the result of both efficiency increase and specific emissions.
- The efficiency benefit reduces fuel and therefore a reduction of 144,000 tons of CO₂.
- The capturing of water from the flue gas would mean a recovery of 7.1 million gal per year (21.8 acre-ft per year) of clean water.

This summary is for replacement of 100-1000 HP firetube boiler stock greater than 20 years old in the South Coast AQMD territory.

Introduction

This is the final report for ICAT Grant 04-1 to perform a Field Demonstration of the Prototype Super Boiler. The Super Boiler consists of a firetube boiler with a unique staged furnace design, a two-stage burner system with engineered internal recirculation and interstage cooling integral to the boiler, unique boiler convective pass design with extended internal surfaces for enhanced heat transfer, and a novel integrated heat recovery system to extract maximum energy from the flue gas. With these combined innovations, the Super Boiler technical goals were set at 94% HHV fuel efficiency, emissions on natural gas of <5 ppmv NO_x, <5 ppmv VOC, and <30 ppmv CO (ref 3%O₂), and 50% smaller foot print than conventional boilers of similar steam output. To demonstrate these technical goals, the stated objectives of the project were to select a host site, fabricate and install the Super Boiler, evaluate system performance, and perform a SCAQMD market analysis.

The industrial demonstration site selected was Clement Pappas located in Ontario, California and the boiler size was a 300 HP firetube boiler. The Clement Pappas Company makes canned and bottled, apple, cranberry, and other fruit juices, as well as cocktail mixers and cranberry sauce.

Innovative Technology

GTI and Cleaver-Brooks have developed a new gas-fired steam generation system, the Super Boiler, for increased energy efficiency, reduced equipment size, and reduced emissions. The system consists of a firetube boiler with a unique staged furnace design, a two-stage burner system with engineered internal recirculation and interstage cooling integral to the boiler, unique convective pass design with extended internal surfaces for enhanced heat transfer, and a novel integrated heat recovery system to extract maximum energy from the flue gas (see Figure 1: Schematic Diagram of Two-Stage Super Boiler System)

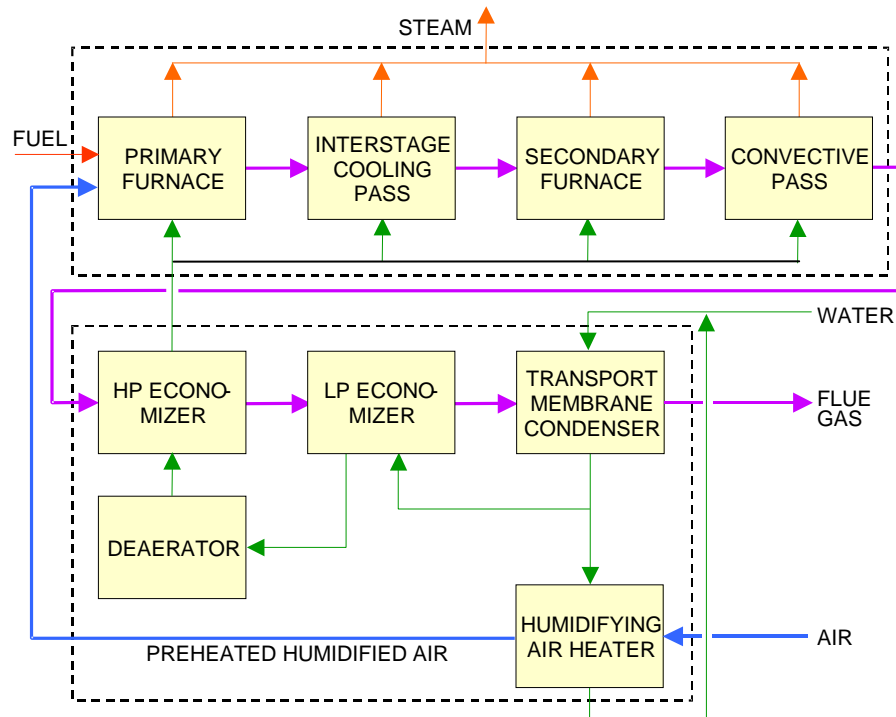


Figure 1: Schematic Diagram of Two-Stage Super Boiler System

For enhanced energy efficiency, the heat recovery system uses a transport membrane condenser (TMC), a humidifying air heater (HAH), and a split-stage economizer to extract maximum energy from the flue gas. The TMC is a new innovation that pulls a major portion of water vapor produced by combustion from the flue gas along with its sensible and latent heat. This results in nearly 100% transfer of heat to the boiler feed water. The HAH improves the effectiveness of the TMC, particularly in steam systems that return a significant amount of condensate to the boiler. In addition, the HAH also humidifies the combustion air to reduce NOx formation.

The split-stage economizer preheats boiler feed water in the same way as a conventional economizer, but extracts more heat by working in tandem with the TMC and HAH to reduce flue gas temperature. These components are designed to work synergistically to achieve energy efficiencies above 92% which is 10 to 12% higher than the typical firetube boiler technology that operates around 80 to 82% efficient.

To reduce equipment size, the Super Boiler's dual furnace design increases radiant heat transfer to the furnace walls, allowing shorter overall furnace length, and also employs convective tubes with extended surfaces that increase heat transfer by up to 18-fold compared

to conventional bare tubes. In this way, a two-pass boiler can achieve heat transfer from the combustion gases that previously required a three or four-pass design. The boiler is consequently up to 50% smaller in footprint, has a smaller shell diameter, and is up to 50% less in weight, resulting in savings in material cost and boiler room floor space.

Finally, the Super Boiler combustion system combines deep air staging, internal flue gas recirculation, interstage cooling, and unique fuel-air mixing technology to achieve low emissions rather than the most widely used method of external flue gas recirculation. This kind of clean combustion is made possible because of the integrated design of the boiler and combustion system which permits precise control of peak flame temperatures in both primary and secondary stages of combustion. The two stage combustion consists of two combustion chambers with a fuel rich primary zone and a staged air secondary zone. The two stages are separated by a convective heat transfer pass that lowers the fuel rich primary gases before the combustion is completed in the secondary zone. The typical technology used today has limitations because it tries to control the peak flame temperatures in one stage with external flue gas and flame temperatures necessary to achieve below 9 ppmv NO_x make combustion hard to maintain and more prone to combustion instability unless enhanced by a combustion technique. Furthermore, this performance is achieved at low excess air throughout the firing range, less than 3% O₂, for optimal energy efficiency, which also distinguishes this technology from current that requires stack oxygen as high as 5 or 6%. This further benefits efficiency.

The individual components of the Super Boiler have already been tested and proven in the laboratory at GTI. The field demonstration at Clement Pappas in Ontario, California has further demonstrated this cutting edge technology in an industrial setting.

ICAT Project

The objectives of this project are to select a host site, fabricate and install the super boiler, evaluate system performance, and perform a SCAQMD market analysis. The tasks for the project are enumerated in Table 1 below.

Table 1. List of Project Tasks

Task No.	Task Name	Milestone	Performed by	ICAT Support
1	Host site selection	Signed Field Test Agreement	Partner/subcontractor	Partial
2	Design and fabrication	Boiler delivered to host site	Partner/subcontractor	Partial
3	Installation	Installation and shakedown completed	Applicant and partner/subcontractor	Partial
4	Testing & evaluation			
4.1	Performance or Parametric testing	Comprehensive performance data collected and processed	Applicant and partner/subcontractor	Partial
4.2	SCAQMD market analysis	South Coast impact analysis completed	Applicant and partner/subcontractor	No
5	Long-term testing	Final report	Applicant and partner/subcontractor	Partial

The performance tests were divided into a short term parametric tests and long term performance tests. The parametric tests quantified efficiency and emissions based on variables such as primary stage stoichiometry, stack excess oxygen levels, ramp up and ramp down performance, and influence of the HAH. Each point for the parametric tests was collected near steady state conditions. The long term testing simply was collection of data during the boiler cycling while carrying the plant's process load and is required to verify emissions and efficiency over time, as well as the ability of this new design to provide reliable, safe operation every day without constant attention from GTI or the plant personnel. Emissions for the parametric tests were measured with a Horiba analyzer that was certified by a relative accuracy test audit performed by a URS Corporation. Emissions for the long term testing was done with an Ecom A+ analyzer with electrochemical cells calibrated twice a month.

Project Results

Task 1 Host Site Selection

GTI worked through R.F. MacDonald (RFM), authorized sales/service rep for project partner Cleaver-Brooks, Inc. to find and conduct preliminary evaluations of potential host sites.

The first site selected was Associated Feed Supply in Turlock, California, was removed from consideration because we needed a South Coast site to meet requirements of project sponsors Southern California Gas and AQMD.

A second prospective site was identified in Los Angeles, American Textile Maintenance, a facility that launders medical garments and linens. However, after correspondence between the site, GTI, CB, and RFM via e-mail and telephone, the project team concluded that the site was not suitable for a Super Boiler demonstration because of limited operating schedule (10 hr/day, 4 days/week).

RFM then identified a third potential host site that is a juice bottling plant in Ontario operated by Clement Pappas & Company (CPC) of New Jersey. The facility (Figure 2 below) had one 600-HP boiler but had space for a second boiler and anticipates future expansion.



Figure 2. Clement Pappas Pictures of Host Site

The Clement Pappas site operated 24 hours a day, 7 days a week, thus offering a good opportunity for annual fuel savings to justify the investment in Super Boiler technology. An initial visit to the facility, attended by GTI and RFM, took place on January 11, 2006. We met with the facility managers, submitted a Field Demonstration Agreement (FDA), and developed an installation scope. At that time, Clement Pappas & Company tentatively agreed to move forward with demonstration of a 300-HP Super Boiler and agreed to the language of the FDA, which stipulates cash and in-kind contributions from the site. Some minor modifications to the FDA were then requested by CB, which were accepted by GTI and CPC.

A follow-up visit by CB and RFM was made on February 20, 2006 to obtain more detailed technical information and prepare a preliminary site layout drawing to confirm that all of the Super Boiler equipment will fit in the available boiler room space. GTI and RFM have reviewed the drawing.

Final approval of the FDA by Clement Pappas was obtained on April 6, 2006, but an amended draft was prepared to add CARB, CEC, and AQMD as sponsors. This amended FDA was sent for approval in April, and was signed by CPC on May 5, 2006.

Task 2 Design and Fabrication

GTI and Cleaver-Brooks completed design and fabrication of the Super Boiler system October 16, 2006. The system consists of the following components:

- Firetube boiler, staged/intercooled design rated for 300 horsepower steam output up to 150 psig;
- Two-stage natural gas combustion system including premixed pilot, flame sensor, and flame safety system;
- Hawk ICS control panel with parallel positioning FAR controls;
- Blow down valves and piping;
- Feedwater valves and piping;
- Steam spool piece, non-return valve, and steam stop valve;
- Level Master water level control;
- Modulating feedwater control valve and bypass loop;
- Gas train and regulator;
- Cain high-pressure economizer;
- Bypass damper;
- Cain low-pressure economizer;
- Transport membrane condenser (TMC);
- Humidifying air heater (HAH);
- Heat recovery control panel;
- Required pumps, sensors, and control valves for heat recovery system;
- Sample coolers;
- Chemical feed system.

The boiler was designed jointly by GTI and CB and fabricated by CB at their production facility in Thomasville, Georgia. The combustion system was designed by GTI and integrated by CB with their integral head design, and was fabricated by CB's Industrial Combustion division in Monroe, Wisconsin. Economizers were purchased from Cain Industries per specifications by CB. The TMC and HAH were designed and manufactured by GTI. Remaining components were purchased from various vendors.

Boiler fabrication was completed on October 11, 2006 and the boiler was moved to the CB test bay for burner installation and combustion pre-testing starting that week. Test-firing and setup of air-fuel ratio (AFR) curves were completed in November 2006. Heat recovery system (TMC/HAH) fabrication, assembly, and leak-testing was completed on October 31, 2006 and these components were shipped to the installation contractor R.F. MacDonald. Photographs of the TMC and HAH are shown in Figure 3. Pictures of TMC and HAH below.



Figure 3. Pictures of TMC and HAH Task 3, Installation

Installation activities began in December 2006 by RFM with the design of a prefabricated heat recovery skid (HRS) which would contain the two economizers, TMC, and HAH. This activity was delayed for about two months while combustion modifications of the boiler were carried out at the CB facility in Thomasville, Georgia. When that was satisfactorily completed, the boiler and all ship-loose parts were delivered to the RFM rigger's yard on April 4, 2007 and then moved to the RFM facility in Brea, California. RFM completed the layout and piping drawings, resumed construction of the HRS, and procured the exhaust stack, diverter valve, piping materials, steam regulator, steam silencer, and a water flowmeter for the main boiler feedwater. GTI purchased data acquisition (DAQ) hardware (notebook PC and data acquisition modules), completed setup of DAQ software at the host site, verified remote data access, and completed specification of interconnections with CB Hawk ICS control system. GTI's engineer also supervised leak-testing of the TMC and HAH at the RFM shop, after which RFM installed all the prefab piping on the skid. Concurrently, Cleaver-Brooks (CB) continued work on combustion control software programming and GTI completed a draft performance test matrix.

RFM submitted the construction permit applications to the City of Ontario in April, 2007, but that was denied subject to additional documentation from RFM regarding seismic calculations for the HRS support structure and anchorage, reworking of the anchorage method to comply with new State rules, and fuel flow rates calculations. In June 2007, Ontario requested a Building Commission review regarding additional roof penetrations and the impact on community aesthetics (residential area across the road from plant). GTI and RFM worked on possible remedies to this concern including a screen wall on the roof, but then the City dropped the issue and initiated new questions about fire rating, boiler room floor thickness, and plumbing of the boiler feedwater into the boiler house. The City then added requirements for UL inspection and approval and re-stamping of all steam piping from the boiler house to the plant. By the end of August 2007, these issues were all resolved, including an agreement to arrange a UL Field Evaluation within 6 months, and the permit was picked up by RFM on September 4, 2007.

With the permit in hand, RFM began site installation work on September 5, 2007. By the end of October 2007, the following installation jobs were completed:

- Foundation and installation of the heat recovery skid.
- Heat recovery units (economizers, TMC, HAH) installed on skid.
- Boiler set and anchored.
- Steam piping and tie-in to main steam header.
- Pumps mounted and powered.
- Main electrical panel installed and powered up.
- Natural gas and water-side piping completed.

- Exhaust ductwork completed.
- Steam silencer and steam regulator installed for off-line testing.
- Instrumentation installed and signal wiring completed
- Loop checks completed.
- HRS controls setup completed.
- GTI emissions monitoring equipment set up for shakedown.
- Partial setup of rental CEM for long-term monitoring.

Shakedown began in November 2007 with cold testing of the HRS to verify water side integrity and controls operation. The project team verified pilot operation and light off, set up combustion controls, and began firing the boiler in HRS bypass mode. First main flame light off was on November 8, 2007, and the team successfully verified combustion over the full firing range in two-stage mode at that time.

With successful combustion shakedown completed, the team began system operation in heat recovery (HRS) mode. This revealed several additional shakedown issues that needed to be resolved before finalizing boiler setup in the HRS mode and begin the parametric testing:

- Re-routing of TMC and HAH drains to prevent a backflow and flooding of the HAH during shutdown.
- Installation of additional control valve to divert a controlled flow of water downstream of LPE back to HAH because makeup water flow was found to drop very low at intervals.
- Installation of a small surge chamber needed for TMC to absorb fluctuations in TMC water level.
- Relocation of TMC level sensor.
- Repair of several minor leaks.

All of these items were completed by December 21, 2007. An additional issue was identified that required host site action, regarding loss of makeup water pressure at intervals due to a high flow demand to a process vessel. This issue upset the TMC and HAH water levels, disrupting the HRS performance. In discussion between GTI, CB, RFM, and CPC, we agreed on a solution involving installation of a separate surge tank and pump for makeup water, which removed the dependence on city water pressure. This modification was completed by the first week in January, 2008.

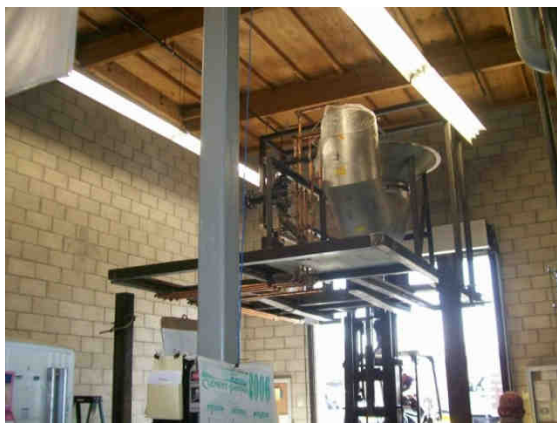
With all these installation items resolved and the boiler installation complete the performance testing began the week of January 7, 2008. Photographs taken by RFM and/or GTI during installation are shown in Figure 4.



Boiler delivered to site



HRS skid moved to boiler room



HRS skid set in position



Boiler set in place below HRS skid



Wiring heat recovery junction box



Humidifying air heater connected

Figure 4. Boiler Installation Pictures



TMC, stack, and reheat line



View from behind existing boiler



Front of Boiler and Access Stairway



HRS Viewed from Left Side



Boiler and HRS Skid Viewed from Back



Welcome Banner from Clement Pappas

Figure 4. Boiler Installation Pictures

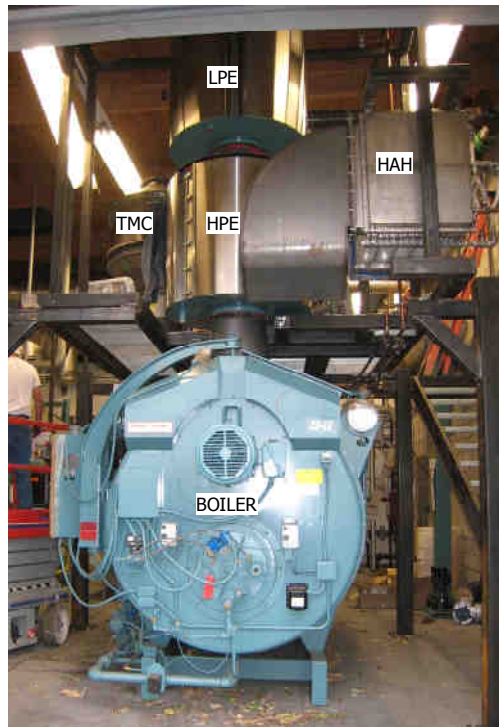


Figure 4. Boiler Installation Pictures

Subtask 4.2 AQMD Market Study

The goal of the market study was to identify the number of potential Super Boiler customers in the South Coast AQMD jurisdiction and estimate the fuel consumption. Secondary goals were to estimate, if possible, the population of boiler sizes and types, total capacity and capacity factor, and total water usage for steam generation. From this data, we intended to estimate the maximum potential impact of Super Boiler commercialization on fuel consumption, NOx emissions, CO emissions, and water consumption. Finally, we intended to estimate the market penetration over a 20-year period and calculate the incremental and total impact of Super Boiler commercialization over that period.

The South Coast AQMD jurisdiction is shown in Figure 5. It encompasses four counties and 814 zip codes (90001 to 94530) in the Southern California Air Basin. The major metropolitan area, boiler market, and source of air emissions is Los Angeles and its suburbs, also including San Bernardino and Riverside. Population in the AQMD jurisdiction represents approximately 46% of the population of California.

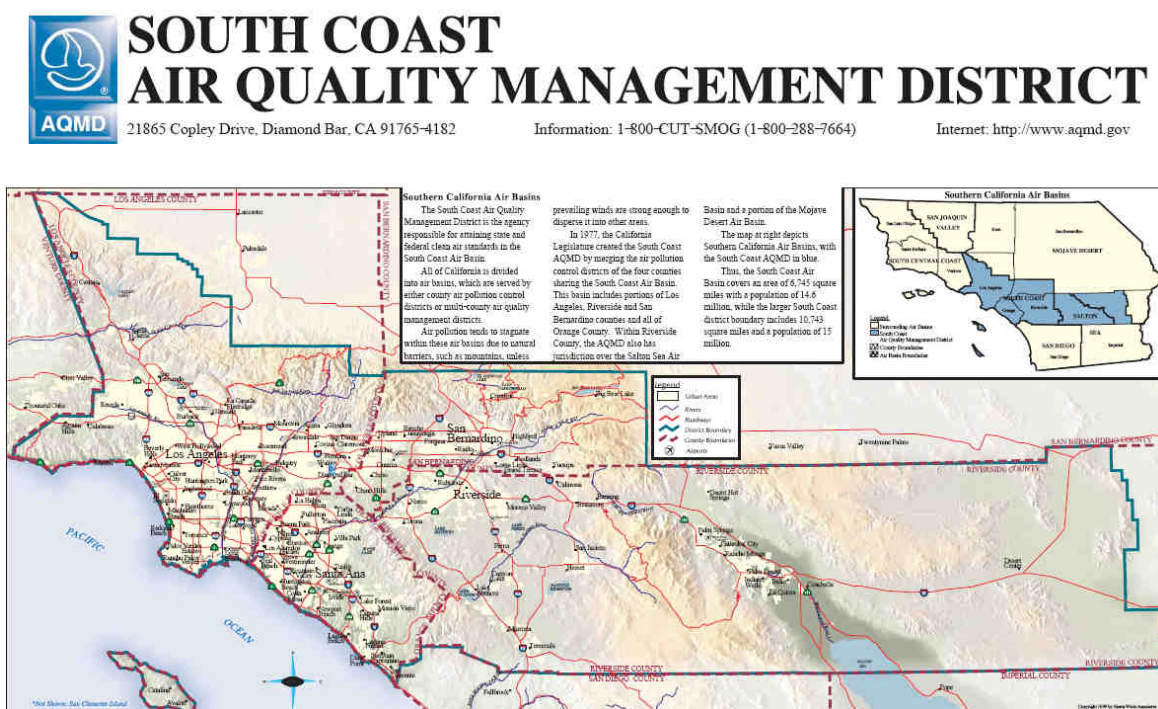


Figure 5. South Coast AQMD Region

GTI purchased a database of manufacturing businesses in California⁴ and identified 21,486 entries within the zip code range of the AQMD, representing 74.8% of the 28,728 manufacturing businesses across the State. Besides manufacturing, package steam boilers are also used by agricultural, commercial, and institutional facilities. For example, 354 of 470 hospitals in California are located in the South Coast AQMD territory, as well as 78 of 399 colleges and universities.

⁴ Manufacturers' News, Inc. (MNI) EZ Select CD-ROM Version 2.5

To identify potential customers for a firetube Super Boiler in the range of 100 to 1000 HP, we used the following procedure:

- Obtained a database of Cleaver-Brooks boilers installed in California since 1960.
- Identified which of those boilers were in the range of 100 to 1000 HP and were installed in the South Coast AQMD territory.
- Identified which of those boilers are more than 20 years old and thus highest priority for replacement.
- Obtained sales data from American Boiler Manufacturers Associations (ABMA) for natural gas firetube boilers installed in California.⁵
- Identified boilers in Cleaver-Brooks and ABMA databases with identical filters (1990-2008, 100-1000 HP, gas only, fire tubes) to estimate Cleaver-Brooks market share.

Installed Base

As a result of the data filtering, we identified 419 businesses in the South Coast AQMD currently using 574 gas-fired CB firetube steam boilers installed since 1960. Of these boilers, 372 (65%) are more than 20 years old and thus likely the first in line for replacement. The total capacity of all the installed CB boilers is 170,796 horsepower (6,832 million Btu/h input), with a mean boiler size of 298 horsepower. Based on a typical capacity factor of 30% for combined industrial and commercial customers, the expected annual natural gas consumption is 18.0 trillion Btu (TBtu). Of these CB boilers, those which are 20+ years old and thus first in line for possible replacement have a total capacity of 91,113 horsepower (3,645 million Btu/h input) and 9.6 TBtu of annual gas consumption.

However, these numbers represent only CB boilers. From a comparison of CB and ABMA sales figures for gas or gas/oil-fired firetube boilers in the range of 100 to 1000 HP since 1990, CB has an estimated market share of 87%. However, this is misleading since many boiler companies do not report to ABMA and hence the CB boiler market share is likely closer to 50%.

After making an adjustment to cover all boiler vendors, our estimate for the total installed base of gas-fired 100-1000 HP firetube steam boilers within AQMD comprises 341,592 horsepower for 1148 boilers. Estimated natural gas consumption for the broader boiler population is 35.9 TBtu, including 19.1 TBtu for those boilers 20+ years old.

Efficiency

Based on current estimated fuel-to-steam efficiency averaging 80%⁶ for boilers in the 100-1000 horsepower range, replacement of the existing 100-1000 HP firetube boiler stock with Super Boilers would ultimately save 13% of natural gas, or 2.5⁷ TBtu annually if all boilers over 20 years old were replaced in the South Coast AQMD-regulated region. With an average California price (weighted industrial and commercial) of \$6 per million Btu,⁸ the annual dollar

⁵ Only 1990-2008 data available.

⁶ Derived from data in "Characterization of the U.S. Industrial Commercial Boiler Population," report to Oak Ridge National Laboratory by Energy and Environmental Analysis. May 2005.

⁷ $19.2 * 0.13 = 2.5$

⁸ http://tonto.eia.doe.gov/dnav/ng/ng_pri_sum_dcu_SCA_m.htm. Weighted average of industrial and commercial delivered prices for July 2008.

savings from replacement of existing firetube boilers over 20 years old with Super Boilers would ultimately save \$15.0 million in natural gas costs.

Emissions

Based on California Air Resources Board emissions data,⁹ total NOx emissions from natural gas boilers in the South Coast AQMD in 2010 is projected at 1,065 tons per year, and CO emissions at 1,232 tons per year. From the estimated fuel consumption for the same market, average NOx and CO output for natural gas-fired boilers in the AQMD is about 29.7 and 34.3 tons/TBtu input for NOx and CO, respectively. However, new regulations will limit NOx emissions to 9 ppmv by 2013, reducing the baseline NOx emissions to an estimated 203 tons per year, while total CO emissions are unchanged at 1,232 tons per year. Limited to boilers more than 20 years old, the projected totals are 108 tons per year of NOx and 657 tons per year of CO.

The Super Boiler has been shown capable of reducing average emissions to 3.1 ton NOx (5 ppmv) and 7.4 ton CO (20 ppmv) per TBtu fuel input. Although replacement of the older boilers would presumably have a greater impact because of more stringent permitting rules for newer boilers, detailed analysis of these populations to elucidate this varying impact is beyond the scope of this project. If we assume replacement of all South Coast AQMD boilers over 20 years old with Super Boilers, the resulting annual emissions would be 59 tons of NOx and 142 tons of CO, which translates to avoidance of 49 tons of NOx and 515 tons of CO. These reductions are the result of both efficiency increase and specific emissions reductions in the two-stage version of Super Boiler that is being demonstrated in Ontario, California.

CO₂ emissions, although strictly speaking are dependent only on efficiency, must also be discussed here. Based on a typical CO₂ emissions rate of 0.0580 tons per million Btu of natural gas fired¹⁰, the current AQMD natural gas firetube boiler population over 20 years old produces 1.11 million tons of CO₂ annually. Replacement of the 20-year-plus population with Super Boilers would reduce this to 0.96 million tons, for a savings of 144,000 tons of CO₂.

Water Recovery

Water savings also result from use of the Super Boiler because the TMC extracts water vapor from flue gas to displace boiler make-up water. The amount of water vapor extraction depends on site-specific and seasonal factors such as water temperature, make-up water rate available for the TMC, and steam pressure. Based on GTI field experience and calculations for a variety of prospective sites, our estimates are 25% average water extraction for industrial customers and 10% for commercial customers. Boilers firing at 80% efficiency generate about 0.334 tons steam per million Btu fuel input, and we estimate a composite average make-up water requirement for industrial and commercial firetube boilers at 40% of steam output.¹¹ Based on a typical water vapor content of 0.099 lb H₂O per scf of natural gas fired, previously estimated fuel usage data for 100-1000 hp AQMD boilers older than 20 years (19.1 TBtu/year), and typical recovery rates for industrial and commercial boilers, replacing all these boilers in AQMD with Super Boilers could recover 47.3 million gallons per year (145 acre-ft per year) of clean water equivalent in purity to RO water. However, this is impractical since only 10-20% of all boilers in this area have sufficient makeup water available to recover the aforementioned water savings. Hence, if 15% of all 100-1000 hp firetube boilers older than 20 years were replaced with Super Boilers, 7.1 million gal per year (21.8 acre-ft per year) of clean water would be recovered.

⁹ <http://www.arb.ca.gov/app/emsinv/fcemssumcat2006.php>

¹⁰ North American Combustion Handbook Volume 1, Third Edition

¹¹ Derived from data in "Characterization of the U.S. Industrial Commercial Boiler Population," report to Oak Ridge National Laboratory by Energy and Environmental Analysis. May 2005.

Summary of Replacement Scenario

The market data for replacement of existing 100- to 1000-HP firetube boiler stock in AQMD territory are summarized in Table 2 below. Both overall and 20+ year old boilers are shown to highlight the magnitude of the near-term replacement market.

Table 2. AQMD Boiler Market (100-1000 HP, Firetube) Based on Existing Population

	All boilers	Boilers >20 years old
CURRENT STOCK		
Number of boilers	1148	744
Total installed capacity, horsepower	341592	182226
Total installed capacity, million Btu/h	13664	7289
Mean capacity factor, %	30	30
Annual gas usage, TBtu	35.9	19.1
Annual NOx emissions, tons	203	108
Annual CO emissions, tons	1232	657
Annual CO ₂ emissions, thousand tons	2082	1111
Annual water usage, acre-ft	3538	1887
POTENTIAL WITH SUPER BOILER SUBSTITUTION¹²		
Annual gas usage, TBtu	31.2	16.7
Annual NOx emissions, tons	111	59
Annual CO emissions, tons	266	142
Annual CO ₂ emissions, thousand tons	1812	966
Annual water usage, acre-ft	3497	1865
POTENTIAL SUPER BOILER BENEFITS		
Annual fuel savings, TBtu	4.7	2.5
Annual fuel cost savings, \$ million (2008\$)	\$28.0	\$14.9
Annual NOx savings, tons	92	49
Annual CO savings, tons	966	515
Annual CO ₂ savings, thousand tons	271	144
Annual water savings, acre-ft	41	22

Market Phase-In Plan

Cleaver-Brooks will need 6-12 months of reliable, safe operation before they consider commercializing the product. Once that period has passed with favorable results, it is estimated that commercialization will take 18-36 months (design and manufacturing drawings for all boilers sizes 100-1000 HP, preparation of sales literature, market research, lab testing, etc.). Hence we estimate commercialization between January 2012 and June 2013, assuming safe, reliable operation in 2009. Of course, if safe reliable operation is not attained, commercialization would be further delayed.

For the case of commercialization in January 2012, our forecast assumes that, in addition to replacement of the existing population, economic growth would result in additional boilers installed for new industrial or commercial facilities or expansion of existing facilities. Assumptions include the following:

¹² Assuming complete replacement of indicated boiler population.

- Existing boiler stock is replaced at 1% per year starting with the oldest boilers.
- All existing boilers not replaced are candidates for retrofit with heat recovery systems at a rate 3% per year.
- Annual industrial growth of 2.0% adds boilers for new or expanded customer facilities.
- Market penetration for entire systems (boiler plus heat recovery) will start at 5% of new CB firetube orders and increase to 90% by 2020.
- Market penetration for heat recovery retrofits will start at 10% of entire market (not CB only) and increase to 34% by 2020.

Table 3. Projected Phase-In of Super Boiler Technology in AQMD

CALENDAR YEAR	2012	2013	2013	2014	2015	2016	2018	2020	TOTAL
Units installed									
Replacement	1	1	1	1	2	2	3	8	19
New/expansion	1	3	5	7	10	12	15	40	93
Retrofit	3	4	5	6	7	8	9	22	64
TOTAL	5	8	11	14	19	22	27	70	176
Incremental annual savings									
Fuel, BBtu	20	33	45	57	77	90	110	285	717
Fuel, \$1000	\$122	\$195	\$268	\$342	\$464	\$537	\$659	\$1,708	\$4,294
Water, acre-ft	1.2	1.9	2.6	3.3	4.5	5.2	6.4	16.6	41.8
NOx, tons	0.16	0.32	0.48	0.64	0.96	1.12	1.44	3.83	8.93
CO, tons	1.68	3.37	5.05	6.73	10.10	11.78	15.15	40.40	94.27
CO ₂ , tons	1,179	1,886	2,594	3,301	4,480	5,187	6,366	16,505	41,499
Cumulative savings									
Fuel, BBtu	10.2	46.8	122.0	248.0	441.2	717.7	1,093.8	1,667.2	
Fuel, \$1000	\$61	\$281	\$732	\$1,488	\$2,647	\$4,306	\$6,563	\$10,003	
Water, acre-ft	0.6	2.7	7.1	14.5	25.7	41.9	63.8	97.3	
NOx, tons	0.08	0.40	1.12	2.39	4.47	7.58	11.96	18.98	
CO, tons	0.84	4.21	11.78	25.25	47.14	79.96	126.26	200.33	
CO ₂ , tons	589	2,712	7,074	14,383	25,583	41,617	63,428	96,674	

Benefits accrue over time so that by 2020, a total of 176 Cleaver-Brooks Super Boiler installations or retrofits will be completed in SCAQMD territory. The annual benefits, as shown in Table 3, will increase to 717 BBtu reduction in natural gas use, 42 acre-ft of treated water saved, 8.9 tons NOx and 94.3 tons of CO emissions avoided, and 41,499 tons of CO₂ avoided. Annual fuel cost savings are estimated to hit \$122,000 at the end of the first year and increase to \$4.3 million per year by 2020. By that time, the cumulative savings will have added up to 1667 BBtu natural gas, 97 acre-ft of water, 19.0 tons of NOx, 200 tons of CO, 96,674 tons of CO₂, and \$10.0 million in avoided fuel costs.

These projections do not take into account the following, which could result in additional benefits:

- Licensing two-stage boiler technology to multiple manufacturers.

- Cost savings to end users from NO_x or CO₂ credits or other incentives.
- Cost savings from reduced usage of treated water.

Subtask 4.1 Parametric Testing

In preparation for parametric performance testing, the project team first attempted to set up the combustion curve in heat recovery (HR) mode to obtain 4 to 5 ppmv NO_x at less than 3 vol% O₂. The project team also delivered operating manuals to CPC and service provider R.F. MacDonald (RFM), and conducted initial training of RFM and CPC personnel. Concurrently, GTI hired the independent company URS Corporation to certify the project's Horiba analyzer for NO_x, CO, CO₂, and O₂ monitoring via a relative accuracy test audit (RATA) as required for performance testing.

For the RATA test, the boiler was operated at constant load. The URS on-site technician reported that the Horiba analyzer passed all tests, which was later confirmed in a printed report and presented in the appendices. A summary of the results are presented in Table 4 below. This table represents emissions data from the Super Boiler while operating at a constant 9,385 scfh natural gas input rate where data from the reference analyzer and the Horiba analyzer are recorded every 30 minutes for a four hour period and then averaged.

Table 4.-Summary of CEMS RATA Results, February 19, 2008

Measured Parameter	Units	Reference Analyzer Average	Horiba Analyzer Average	Relative Accuracy	Allowable Rel. Acc.	Status
NO _x	ppmv	4.04	4.33	9.3%	20%	Pass
CO	ppmv @ 3% O ₂	8.32	5.00	6.9% ¹³	NA	
CO ₂	%	10.62	10.73	1.3%	NA	
O ₂	%	2.09	2.21	5.7%	10%	Pass

The project team also hosted a TÜV SÜD America field investigation as required by the City of Ontario as one step to obtain an operating permit for the host site. TÜV SÜD America submitted a report to GTI, CB, and the City of Ontario documenting completion of the Field Investigation.

Following the RATA test, GTI proceeded with parametric testing in accordance to the procedure outlined in their literature titled "SAMPLING AND ANALYTICAL QA/QC SUMMARY" presented in the appendix of this report. To perform the tests it required venting steam as needed to maintain desired firing rate while the existing 600HP boiler continued providing steam to facility. GTI conducted nine parametric tests in February and the remaining 18 tests in March, 2008, according to the updated test matrix submitted with the Jan-Mar 2008 quarterly report. A summary of parameters tested:

- Firing rate 33 to 107% of nominal capacity
- Stack O₂ 1.3 to 3.1 vol%
- Primary zone "Staging Index" value, expressed as the ratio of primary zone total hydrocarbons (THC, ppmv) to firing rate (% capacity), 130 to 532.

¹³ The CO Relative accuracy had a difference of 3.5 in raw ppm, which resulted in a RA of 41.7%. The reported RA is based on the emission standard of 50 ppm @ 3% O₂.

- HAH providing -13° to +16°F combustion air temperature change¹⁴ and +7° to +28°F dew point increase
- Make-up water rate 40% to 145% of Super Boiler feedwater rate.¹⁵

During the parametric testing, controlling the make-up water fraction as desired was problematic because both boilers are supplied from a common feedwater tank and the existing boiler was needed to satisfy the facility steam demand while the Super Boiler was venting steam to reach planned firing rates. Because all of the make-up water for both boilers passes through the TMC, we were so far unable to set this rate at constant value under all conditions. This can be addressed in the future if time and funding permits, depending on the conclusions from the existing data.

The results of the Task 4 subtask 4.1 performance tests are shown in Table-5. The test matrix, using a Box-Behnke design, was slightly modified from the version submitted earlier with the Jan-Mar 2008 quarterly report based on field conditions. For each of the four parameters, the nominal target levels (L, M, or H) are shown in the top three rows. For each test and parameter, the corresponding target level is given in the left column and the actual measured value is shown in the right column.

Firing rate and stack O₂ were held within 10% of target values, and THC/FR was held within 25% of target values. The parameter THC/FR is a staging index based on the ratio of the total hydrocarbons measured in the primary zone to the burner firing rate. However, as described earlier, it was not possible to regulate make-up water fraction to the Super Boiler during normal plant operation when the existing boiler was supplying steam to the process. This is evidenced by the make-up water rate in effect exceeding 100% of the Super Boiler steam output in some cases, e.g., when both boilers are firing and the condensate return rate is low. At this time Clement Pappas operated on a 24/7 schedule, so there were no downtimes during which to operate the Super Boiler independently.

¹⁴ In three of the tests, the HAH water flow was stopped, and although this was expected to result in zero air temperature change, a cooling effect (negative air temperature change) was observed. This was attributed to evaporative cooling from water supplied to the membrane tubes by natural suction driven by the evaporative mass transfer.

¹⁵ Make-up water rate in excess of 100% denotes condition where the existing 600HP boiler is drawing a large feedwater demand from the common feedwater tank while the Super Boiler is venting steam, and thus the make-up water passing through the TMC exceeds the Super Boiler feedwater demand, as detailed in the text.

Table-5. Updated Task 4.1 Performance Test Matrix and Measured Data

Key	Firing rate (% capacity)		Staging Index (THC/FR) ¹⁶¹⁷		Stack O ₂ (vol%)		Make-up water (% of boiler feed water) ¹⁸		HAH effect, dewpt change (°F)	
L	33		175		1.5		50		0	
M	67		335		2.2		--		--	
H	100		520		3.0		100		+23	
Matrix#										
1	L	33	L	139	L	1.5	L	145	H	+22
2	L	35	H	487	L	1.6	L	41	H	+25
3	L	33	M	357	M	2.1	L	132	H	+23
4	L	34	H	479	H	3.0	L	42	H	+26
5	L	34	L	130	H	3.1	L	46	H	+26
6	M	65	M	333	L	1.5	L	40	H	+22
7	M	67	L	183	M	2.1	L	78	H	+15
8	M	68	M	316	M	2.1	L	76	H	+13
9	M	66	H	520	M	2.3	L	41	H	+21
10	M	65	M	335	H	3.0	L	41	H	+23
11	H	106	L	170	L	1.3	L	50	H	+21
12	H	102	H	532	L	1.4	L	51	H	+12
13	H	101	M	299	M	2.1	L	51	H	+12
14	H	105	L	170	H	2.9	L	47	H	+26
15	H	101	H	492	H	3.0	L	52	H	+12
16	L	35	M	308	M	2.1	L	43	L	+10
17	M	67	M	304	M	2.2	L	53	L	+7
18	H	107	M	287	M	2.2	L	49	L	+7
19	L	35	M	348	M	2.2	H	83	H	+28
20	M	65	M	268	M	2.4	H	109	H	+20
21	H	105	M	304	M	2.1	H	62	H	+21
22	L→M	33→68	M	343	M	2.1	L	77	H	+14
23	M→H	64→107	M	344	M	2.2	L	36	H	+21
24	H→M	104→65	M	210	M	2.3	L	78	H	+23
25	M→L	63→34	M	332	M	2.2	L	78	H	+34
26	Startup	0→27	--		--		L	146	H	+18
27	Shutdo wn	104→off	M	194	M	2.9	L	19	H	+15

Efficiency – Impact of Make-Up Water

Although the limitation described above restricted our ability to determine statistical significance of make-up water fraction between high and low target values, we were still able to obtain very

¹⁶ THC = Total hydrocarbons in primary zone, ppmv; FR = firing rate, % of capacity.

¹⁷ Value range ±25%.

¹⁸ See note † on previous page.

useful information about the impact of make-up water on efficiency, as shown in Figure 6. Two different efficiency metrics – thermodynamic efficiency¹⁹ and fuel-to-steam conversion,²⁰ both calculated on a higher heating value (HHV) basis – are shown.

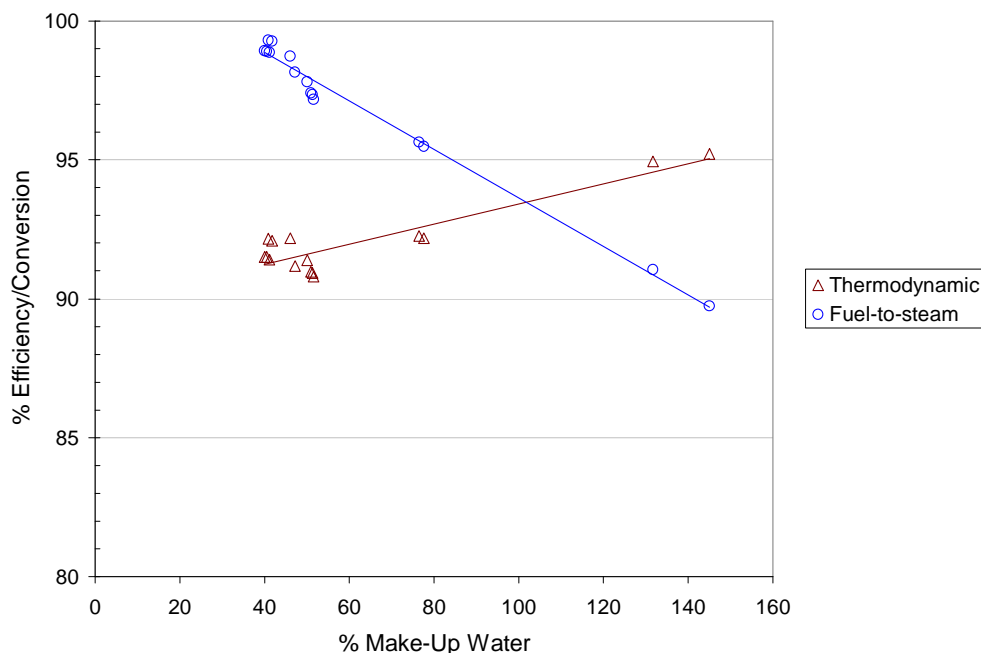


Figure 6. Impact of Make-Up Water on Efficiency

Thermodynamic efficiency, which reflects the enthalpy balance around the boiler envelope, increases with higher make-up water, reflecting the increasing ability of the TMC to remove sensible and latent heat from the flue gases. As the flow of cool water through the TMC increases, more water vapor can be condensed from the flue gas and the incremental benefit of the TMC increases as well. In cases where the make-up water exceeded 100% of the Super Boiler feedwater rate (*i.e.*, the Super Boiler was at low fire and the backup boiler was providing most steam to the plant), the thermodynamic efficiency reached 95%.

Fuel-to-steam conversion is more meaningful to the boiler owner than thermodynamic efficiency because it is directly proportional to the facility's fuel usage for a given steam demand, and thus directly impacts economic benefit. In this regard, the data shows that energy conversion from fuel to steam is higher at lower make-up water flow because the higher-temperature condensate return adds more enthalpy to the system compared with cool make-up water. When ambient air temperature, water temperature, and condensate return rate are high, fuel-to-steam conversion can approach or even exceed 100%. As shown in Figure 6, steam enthalpy output was nearly 99% of fuel enthalpy input when total make-up water was below 50% of the Super Boiler feedwater demand.

¹⁹ Thermodynamic efficiency is defined as $(Q_{\text{steam}})/(Q_{\text{fuel}} + Q_{\text{make-up water}} + Q_{\text{air}} + Q_{\text{condensate return}}) \times 100$ where Q represents the heat values for the different components..

²⁰ Fuel-to-steam conversion is defined as $(Q_{\text{steam}})/(Q_{\text{fuel}}) \times 100$ where Q represents the heat values for the different components..

Overall, in the parametric tests, the Super Boiler system logged a steady-state mean thermodynamic efficiency of 92.1%. Fuel-to-steam conversion ranged from 89.7 to 99.3% with a mean of 97.0%, depending primarily on the amount of returned condensate and to a minor extent on the firing rate. The flue gas temperature exiting the boiler stub averaged 362°F with a dew point of 136°F, and after the TMC, the final stack temperature averaged 125°F with a mean dew point of 120°F. At the ambient conditions present during the parametric tests (70-75°F make-up water, 86-108°F air at boiler inlet), both fuel-to-steam conversion and thermodynamic efficiency were approximately 94% when make-up water fraction was 100%.

Efficiency – Impact of Combustion Air Humidification

The HAH functions to provide additional water flow to the TMC by transferring some of the heat from hot water exiting the TMC and LPE to combustion air and recycling the cooled water back to the TMC midpoint. One of the ways the HAH does this is to evaporate a portion of the hot water into the air stream and use that evaporative cooling to further reduce temperature of the recycled water stream. One of our goals was to evaluate the effectiveness of this evaporative cooling to increase the efficiency of heat recovery, while also reducing NO_x in the boiler by peak flame temperature suppression due to increased combustion air humidity. Tests 16-18 were conducted to determine these effects of air humidification in the HAH by comparing them specifically to tests 3, 8, and 13.

Figure 7 is a plot of thermodynamic efficiency and fuel-to-steam conversion as a function of dew point change in the air exiting the HAH in the six comparison tests listed above. No statistically significant increase in either fuel-to-steam conversion or thermodynamic efficiency from HAH humidification can be claimed from these data.²¹

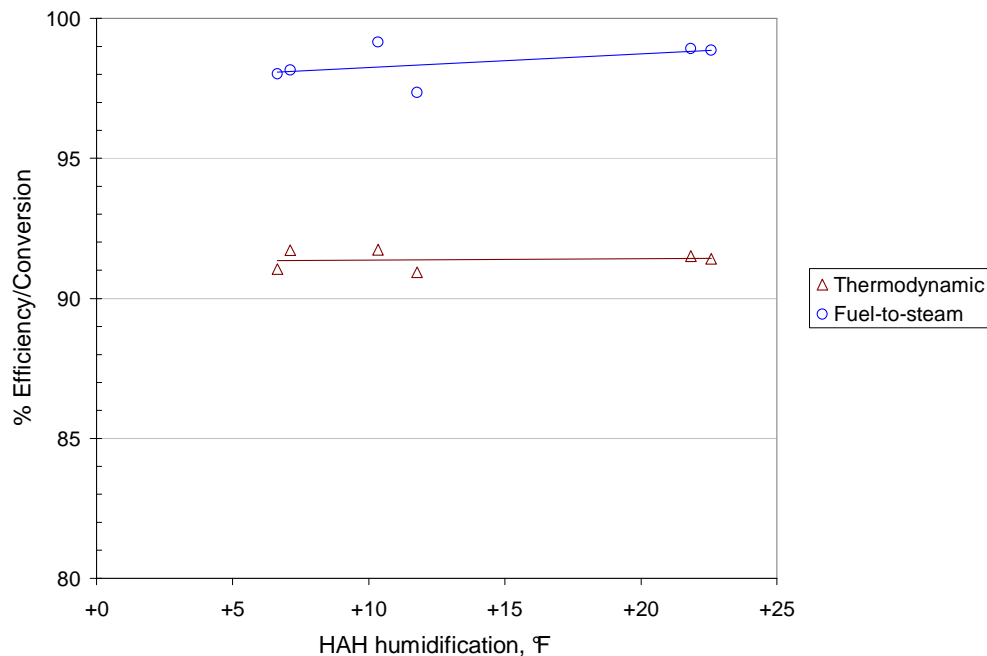


Figure 7. Impact of HAH Dew point Change on Efficiency

²¹ Dew point increase of +16°F correlated with +0.8% increase in fuel to steam conversion and +0.1% increase in thermodynamic efficiency, equal to 1.3 and 0.2 standard deviations of data set, respectively.

Emissions – Impact of Staging Index and Firing Rate

As discussed earlier, we had learned in previous research that NOx emissions²² are strongly correlated to primary zone chemistry, and thus we used Staging Index THC/FR to evaluate results. The Staging Index THC/FR is the ratio of the total hydrocarbons measured in the primary zone to the burner firing rate. The total hydrocarbons are used as an indicator as to how fuel rich the primary zone is operating. The stack NOx emissions can be optimized for a range of THC values. If the THC values in the primary combustion zone raise too high then the stack measured NOx will start to increase and the primary zone combustion may not be able to maintain combustion. If the values for the primary zone THCs are increased above this range then stack NOx will increase and there may not be enough hydrocarbons for complete combustion of the secondary zone. It should also be noted that this optimal range of THC values are dependent on firing range. We plotted data from steady-state Table-5 parametric tests 1 through 15 as a function of THC/FR. Figure 8 shows the ensuing relationship between NOx, firing rate, and THC/FR. NOx ranged from 3.5 to 7.0 with dependence on THC/FR ratio and also on the firing rate relative to capacity. NOx emissions in these tests averaged 4.5 ppmv.

In the same tests, CO emissions²² ranged from 2.5 to 60 ppmv, averaging 12.6 ppmv. Figure 9 shows that the only conditions where CO exceeded 20 ppmv were at low fire and low THC/FR. This reflected the conditions least favorable for complete combustion of the second-stage flame as a low firing rate and relatively leaner primary fuel stream. This suggests that complete combustion can be managed by optimal tuning of the fuel/air ratio controls in the primary stage of combustion during commissioning to keep the primary zone stoichiometry within the desired operating envelope.

²² All NOx and CO emissions are corrected to 3% O₂.

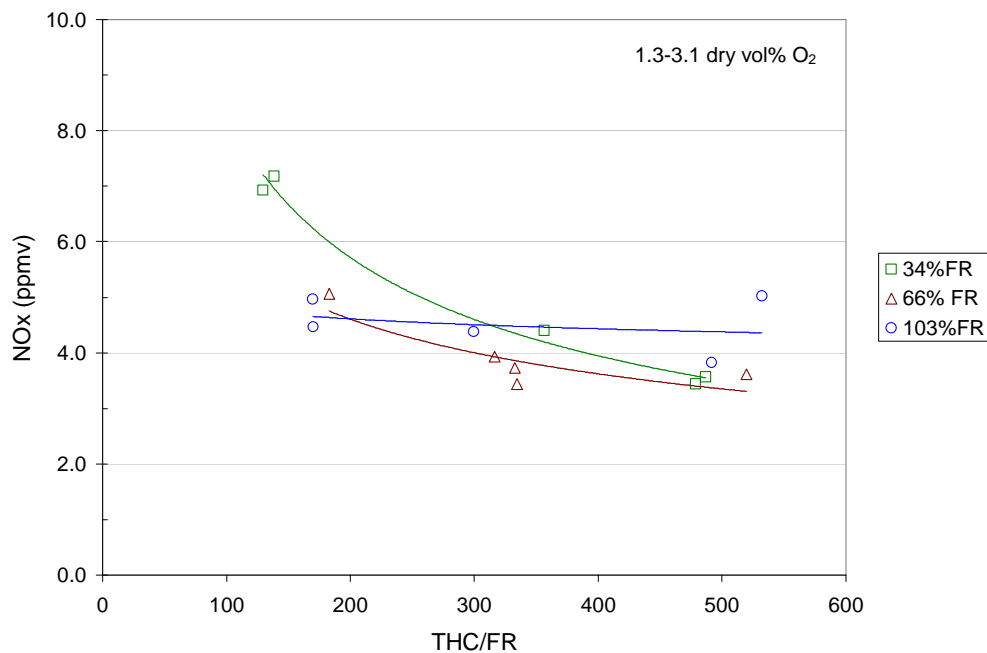


Figure 8. NOx Emissions Data from Steady-State Tests

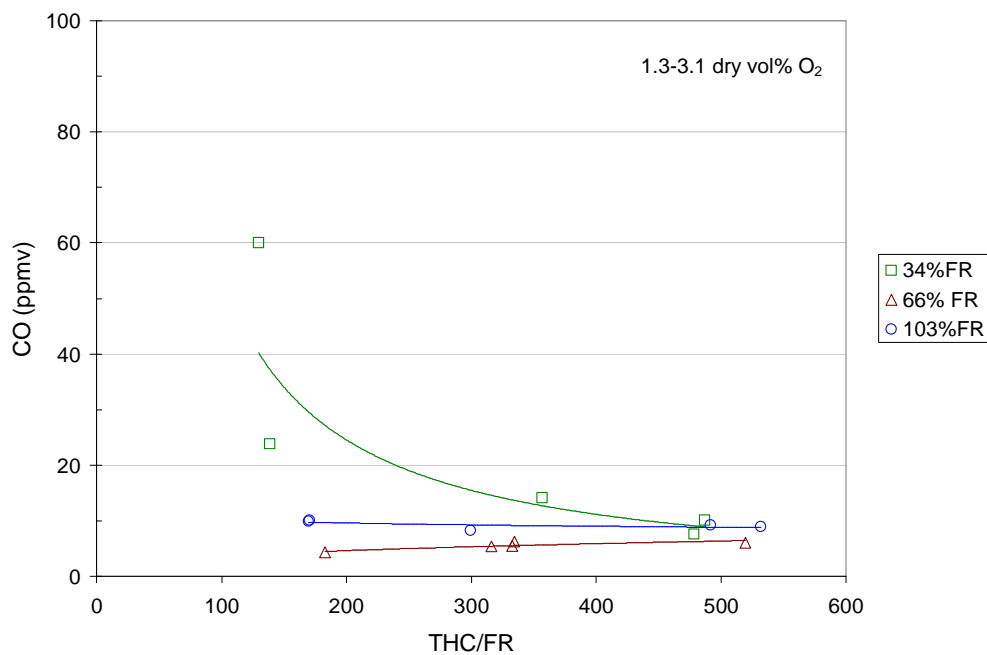


Figure 9. CO Emissions Data from Steady-State Tests

Emissions – Impact of Combustion Air Humidification

As discussed earlier, one of our goals was to determine whether combustion air humidification in the HAH could have a beneficial effect on NO_x suppression. Figure 10 shows data from tests with high and low HAH humidification at low, medium, and high firing rates and a mid-range of THC/FR values. Data at high firing rate was not available with high humidification, but for the low and medium firing rates, the humidification appears to suppress NO_x by 0.3-0.5 ppmv. With the small data set available, this suppression is not statistically significant.²³ However, the HAH is also important to the HRS because it transfers heat from the TMC to the combustion air during times when makeup water flow to the TMC is low. The water temperature in the TMC must be kept lower than the dew point temperature in order for the water in the flue gas to condense on the TMC membranes.

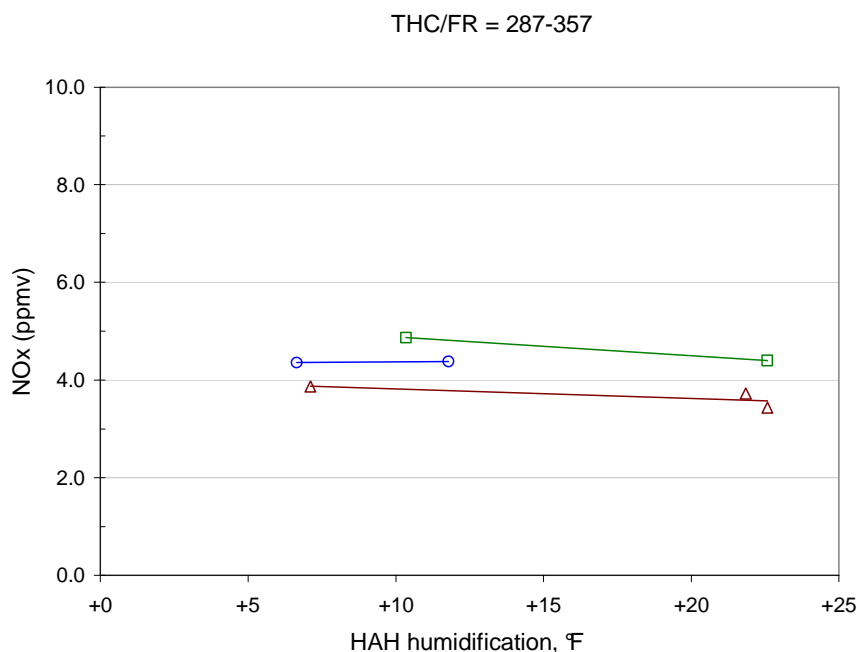


Figure 10. Impact of HAH Dew point Change on NO_x

Startup, Shutdown, and Transitions

As requested by AQMD, six unsteady-state tests (22-27) were performed to evaluate startup, shutdown, and four firing rate transitions.

The cold start sequence consists of a light-off in single-stage mode (primary zone firing under lean conditions) to heat up the recirculation sleeve and primary furnace, followed by an increase in fuel flow to establish substoichiometric conditions in the primary zone and self-ignition in the secondary zone. Figure 11 shows firing rate, steam pressure, NO_x, CO, and O₂ (both in-situ wet O₂ and ex-situ dry basis O₂) data collected in March 2008. Figure 12 shows how the fuel and air valves and variable speed drive (VSD PV%) for the combustion air fan are modulated during the cold start. Figure 12 also shows the gradual increase in stack temperature during the cold start and transition to two-stage firing. During the light-off and single-stage warm-up

²³ Dew point increase of +16°F correlated with -0.47 ppmv decrease in NO_x, equal to 1.0 standard deviations of the data set (68% confidence level).

period, stack O₂ is high at 10% because secondary air flow is established prior to secondary light-off. Once the secondary flame is established, O₂ in the stack drops to the desired 1-3% level.

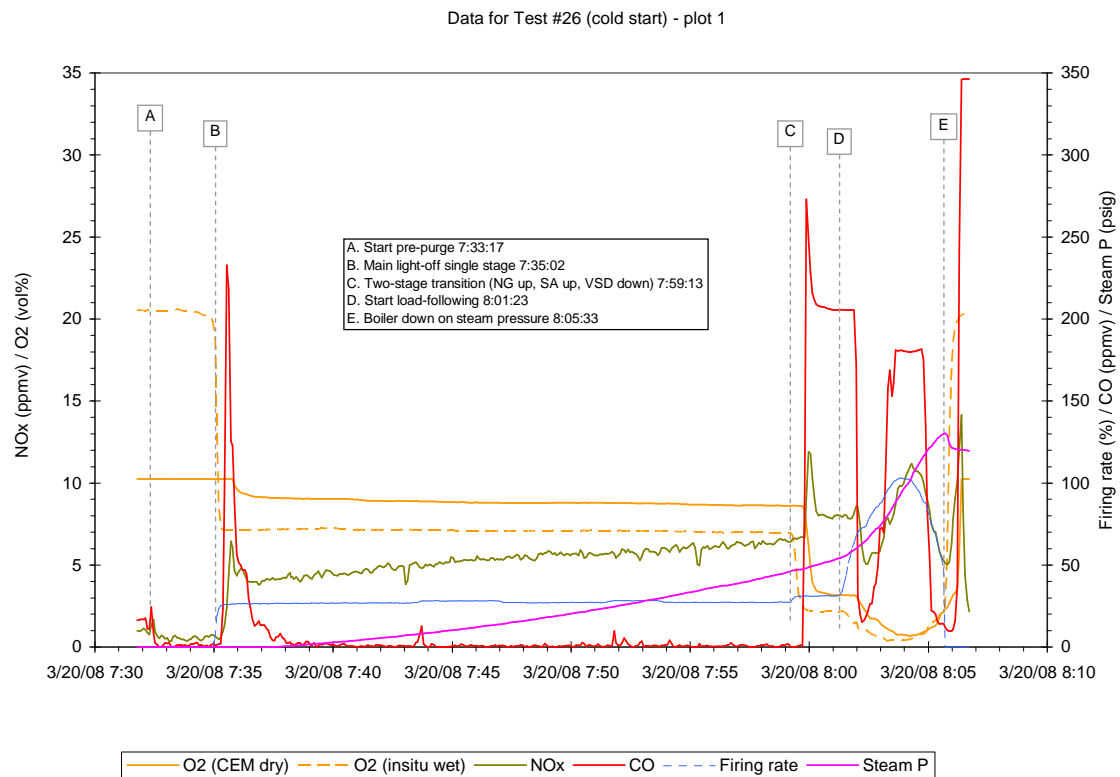


Figure 11. Cold Start Test 26 Showing Firing Rate, Steam Pressure, and Emissions

Data for Test #26 (cold start) - plot 2

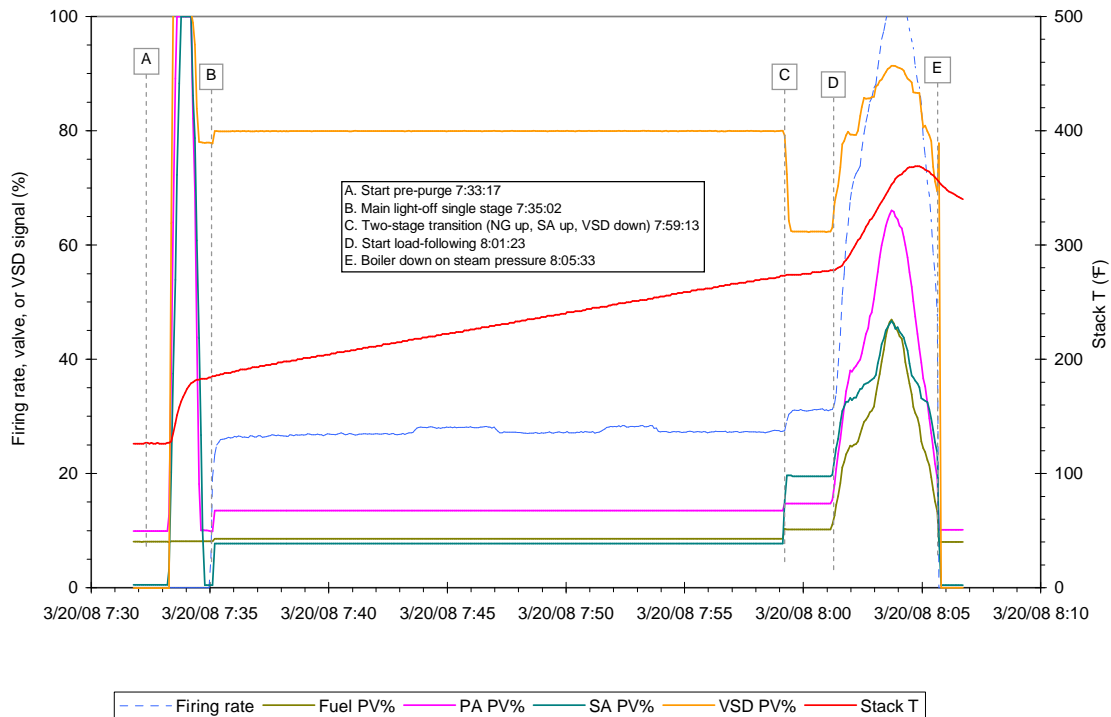


Figure 12. Cold Start Test 26 Showing Control Parameters and Stack Temperature

NO_x rose from 4 to 6 ppmv during the warm-up period and then spiked to 11 ppmv before dropping down into the 5-10 ppmv range when load-following began. CO also spiked to about 205 ppmv during transition to two-stage combustion but dropped to 19 ppmv once secondary combustion was established. The entire process from single-stage light-off to load-following took 29 minutes.

The shutdown sequence begins with shutting the fuel valve and a post-purge cycle that purges any remaining gases from the boiler. This immediately extinguishes both primary and secondary flames. After 20 seconds to purge combustibles out of the boiler, the VSD shuts down. Figure 13 and Figure 14 show data from a hot shutdown sequence on March 18, 2008, and also show pre-purge for another light off three minutes later. NO_x peaked at about 19 ppmv after shutdown, and then quickly declined to zero. CO peaked at a much higher level (it pegged out the CEM at 350 ppmv) and dropped more gradually, reaching 200 ppmv after 2 minutes and 100 ppmv after 3 minutes.

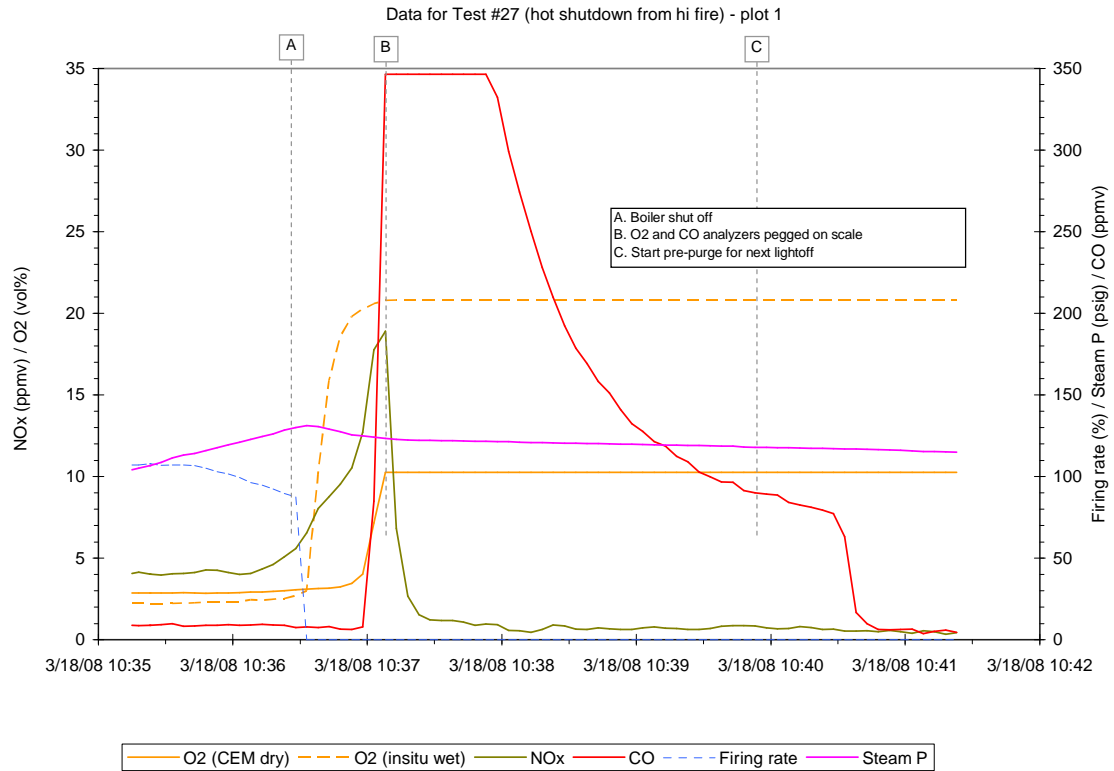


Figure 13. Hot Shutdown Test 27 Showing Firing Rate, Steam Pressure, and Emissions

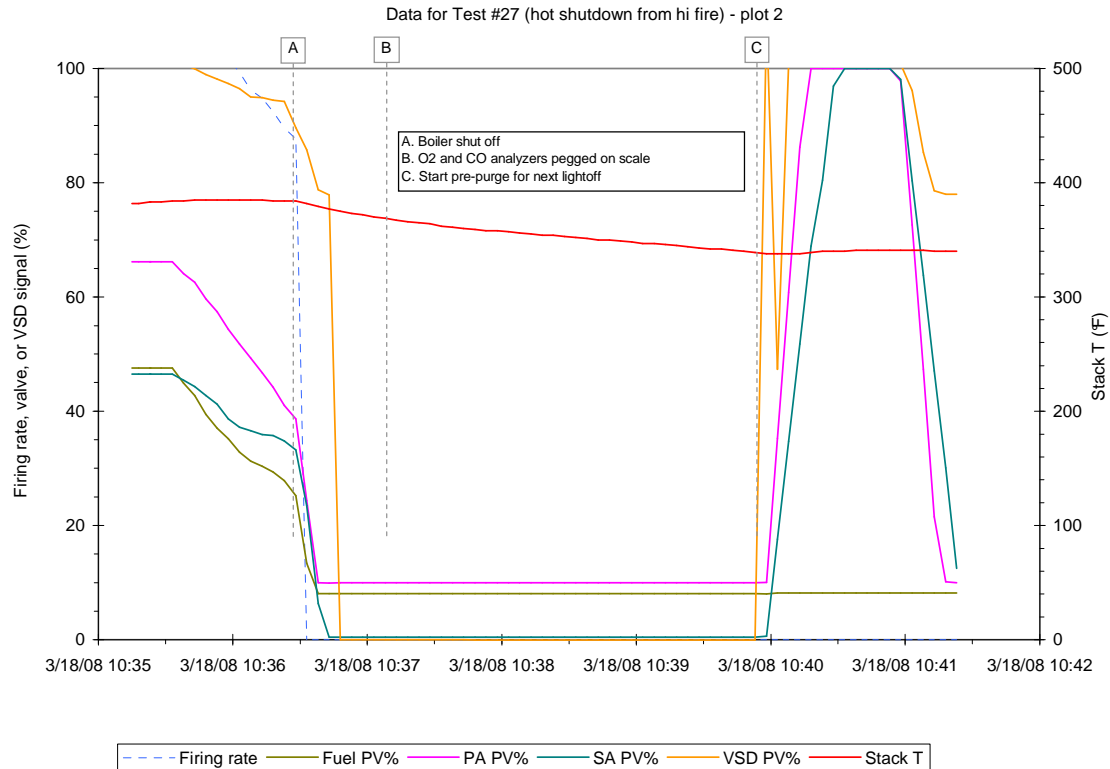


Figure 14. Hot Shutdown Test 27 Showing Control Parameters and Stack Temperature

Data from transition tests 22-25 are also shown below. The firing rate changes were made by manually changing the input value on the touch-screen boiler control panel in auto mode, and so all control outputs were transmitted automatically by the PLC controller to fuel and air valves and fan VSD, reflecting standard operation. Test 22 (low-to-medium fire transition) is shown in Figure 15. Test 23 (medium-to-high fire transition) is shown in Figure 16. Test 24 (high-to-medium fire transition) is shown in Figure 17. Test 25 (medium-to-low fire transition) is shown in Figure 18.

Each transition took 60-100 seconds to complete. In all cases, stack O_2 deviated by no more than 0.7 vol% during the transition. NO_x stayed below 9 ppmv and CO stayed below 35 ppmv in all cases during transition, with final values of 4.5-5.5 ppmv for NO_x and 4-16 ppmv for CO.

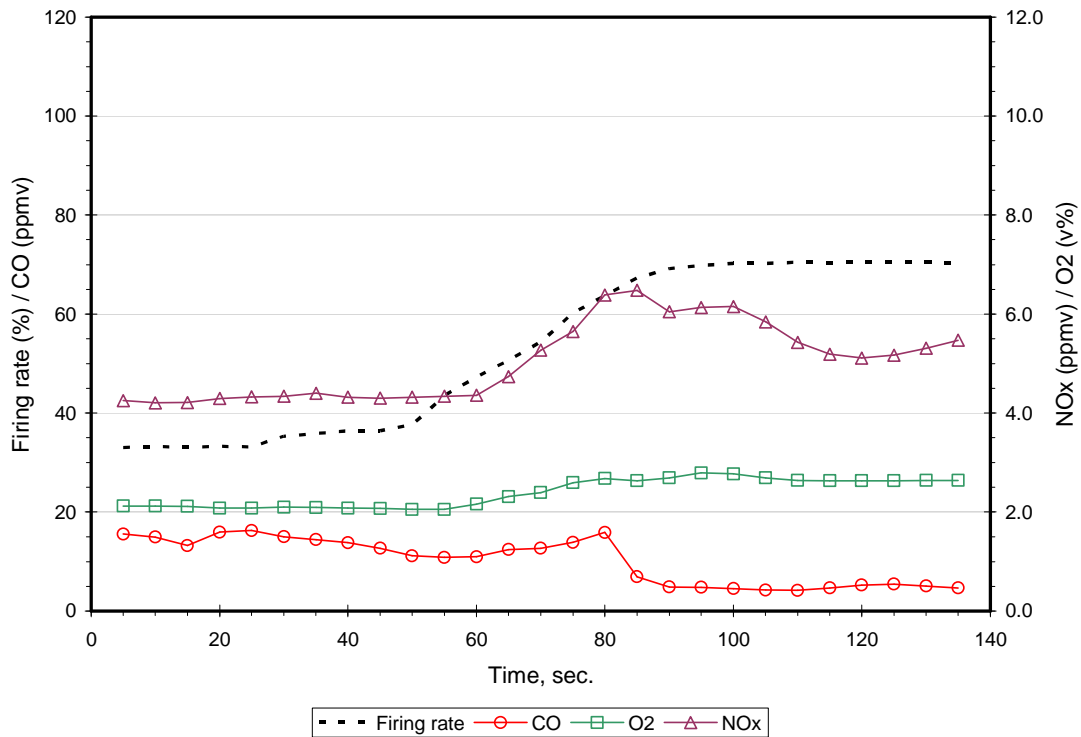


Figure 15. Transition Test 23 (Low-Medium Fire) Data

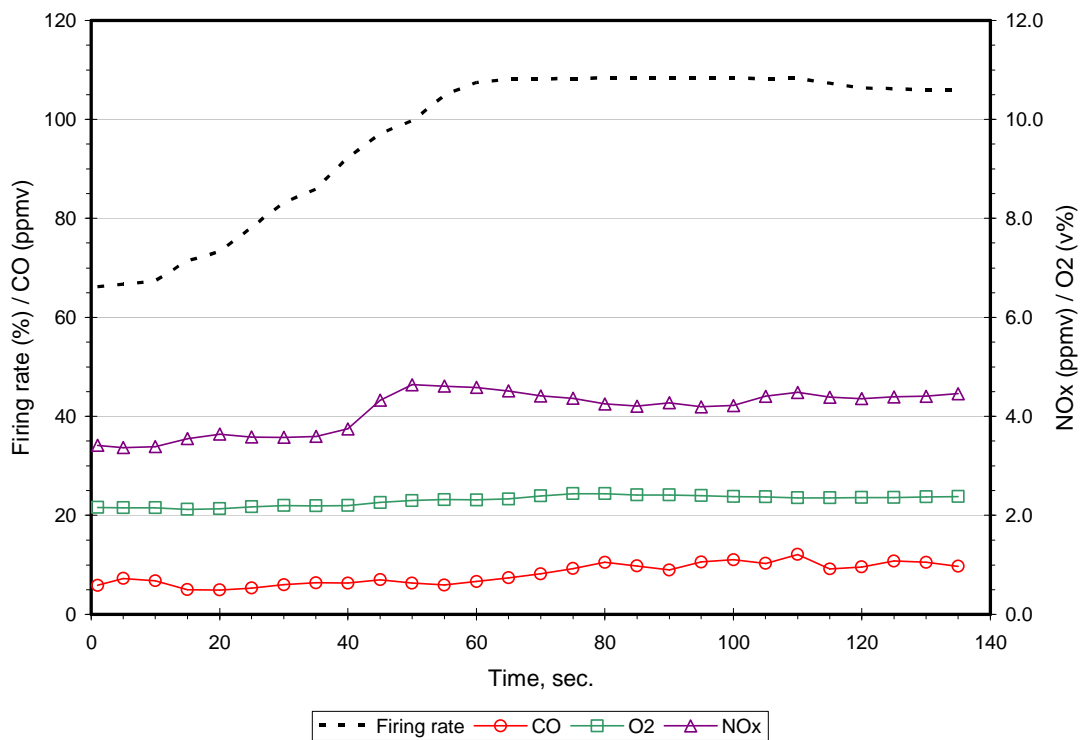


Figure 16. Transition Test 23 (Medium-High Fire) Data

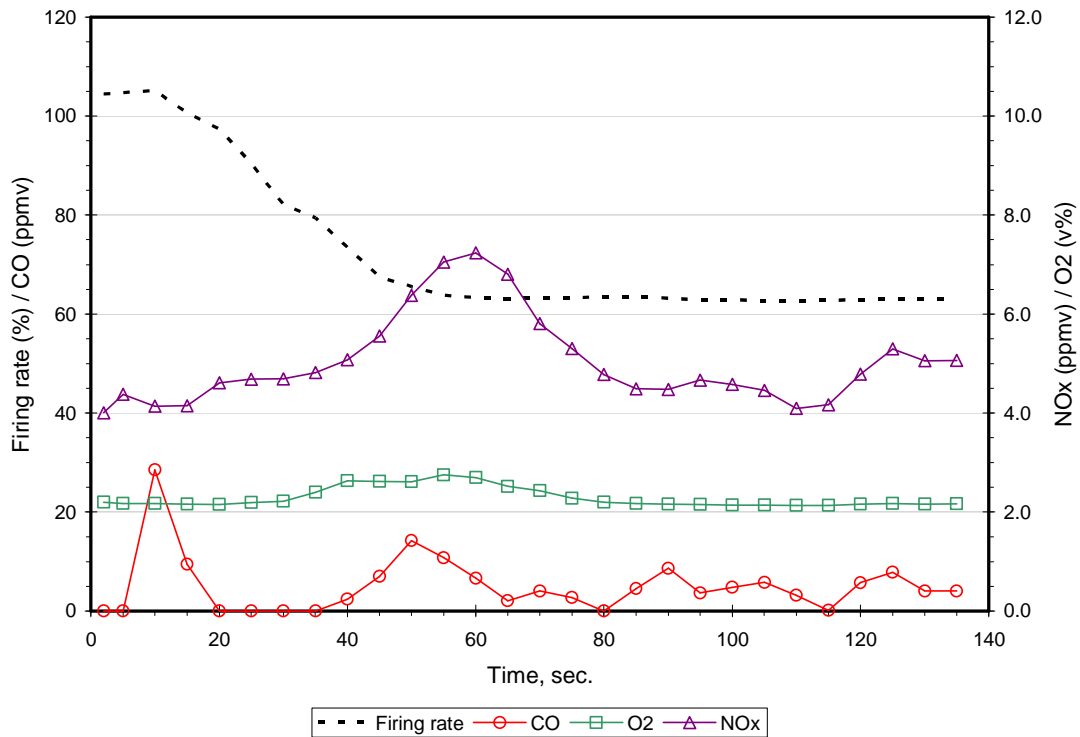


Figure 17. Transition Test 24 (High-Medium Fire) Data

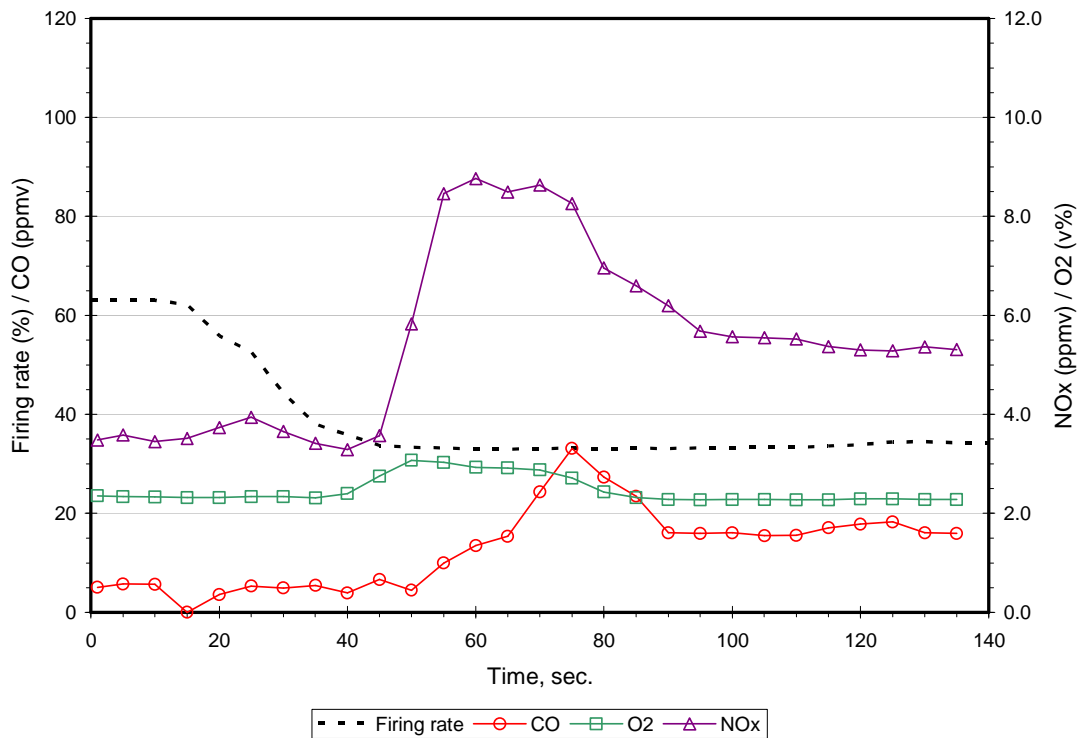


Figure 18. Transition Test 25 (Medium-Low Fire) Data

Task 5 Long Term Testing

The purpose of this task was to monitor critical parameters of the boiler's operation for a half year after the boiler's initial commissioning. Full plant unattended operation of the boiler could not be done until the operating permit was obtained and system shake down was complete. The operating permit was not received until the end of September 2008. The boiler was put into cold storage until the permit was obtained. There were also some issues with the plant's processing equipment where product was getting into the condensate water. This caused further delay of the boiler operation. Because of these two items, actual unattended operation of the boiler to the plant was not accomplished until February 18, 2009.

Despite the inability to have the full 6 months of operation unattended there was several weeks of observed attended operation of the boiler. Based on observations made in a trip to Clement Pappas the week of April 27-May 2, 2008, the boiler was having numerous shutdowns related to low water during sudden large demands of steam loads and low stack measured oxygen. GTI and CB carried out numerous changes to help eliminate the shut downs including installation and set up rear door level sensor, modification of the water level control settings, and set up steam pressure vent and control limits to optimize Super Boiler. After the permit was obtained in September a trip was made to Clement Pappas, the week of October 5, to start boiler operation to the plant. During this week GTI and CB observed a continuation of the low water shutdowns. It was also observed that there was a dark discoloration of the condensate return water. This discoloration was determined to be the juice product from the plant leaking into the condensate water from the heat exchanger used to heat the product. Because of this, it was determined that the boiler should be put into cold storage until the problem was resolved to prevent damage to the Super Boiler.

The week of February 16, 2009 the boiler was brought back on line to start carrying the plant load. The issue of product in the condensate return was resolved by replacement of the plant's heat exchanger. After this issue was resolved the problem with low water shutdowns ceased. This would suggest that product in the condensate going to the boiler was causing the low water shut downs.

There continued to be nuisance alarms for low oxygen in the stack that would occur during burner modulation with the plant load. During modulation to higher firing rates the measured oxygen levels would go down below the set point and then increase during decreased firing rate. The control of air and gas flow during modulation is more critical because this burner technology is able to operate at lower oxygen content levels when compared to conventional technology. To address this issue GTI and CB made some changes to the PLC logic that allowed compensation for the difference in the opening speed between the gas valve and the air control. This scheme was able to greatly reduce the hysteresis taking place during modulation.

Another issue that was causing nuisance shut downs was during pilot ignition. This type of fault can mean that the pilot is not stable and will not stay lit, or the pilot may be strong but the scanner that may not have a good view of the flame. This issue became more noticeable when the steam vent valve was closed. The original purpose for opening the steam vent valve was to prevent low water shut downs of the boiler caused by frequent cycling of the burner. This was accomplished with a regulated vent valve that vented steam when the pressure reached the regulator's set point. This point was set above the boiler's operating pressure but below the boiler's shut off set point. The venting would take place during low or no production times and kept the boiler operating at all times so that it would be ready for a sudden steam demand rather than having to start from the off position. Since the issue of product in the condensate water had been resolved there were no further incidences of low water shut downs so it was decided to keep the steam vent valve closed to reduce wasted steam. This increased the number of

on/off cycling which made the reliability of the pilot more pronounced, but simulated actual operation for this installation.

Something else that made the pilot reliability more of an issue was a decrease in the plant's production. The plant reduced production schedule from 24 hours, seven days a week to 20 hours a day, 5 days a week. During the four hours of no production, the Super Boiler continued to operate so the number of on/off cycles increased. The number of cycles during a 24 hour period could range from 30 to 50.

During the week of February 16 the pilot fuel flow and combustion air settings were optimized to make the pilot more reliable. This helped somewhat but there continued to be nuisance shut downs. During the week of March 23 the pilot combustion air source location was changed from plant compressor to the boiler front windbox or head. The automatic shut off valve for the pilot combustion air was removed. This improved the reliability of the pilot significantly.

Since February 18, 2009 the Super Boiler has been the primary boiler carrying the plant load. Production operation since this time has consisted of 20 hours a day at 3 to 5 days a week. Below is a summary of the operation of the Super Boiler along with the operation time and the site visits (See Table 1 below). Since the Super Boiler has been operating carrying the plant load on February 18, 2009, it has logged in approximately 756 hours of operation time. The operation time is considered time where the burner is firing.

Table 6.-Boiler Operation Summary

Date start	Date ending	Boiler status	Operating hours	Description
February 16, 2009	February 25, 2009	On	89.2	Site visit to get the Super Boiler ready for long term testing and operation
February 26, 2009	March 19, 2009	On	341.8	Super Boiler on line carrying plant load
March 23, 2009	March 27, 2009	On	74.1	Site visit to correct pilot issues and boiler controls
March 28, 2009	April 19, 2009	On	138.1	Super boiler on line carrying plant load
April 20, 2009	April 24, 2009	On	54.2	Site visit to make modifications to the pilot
April 25, 2009	April 30, 2009	On	58.6	Super Boiler on line carrying plant load

Emissions-Impact during load following

A detailed discussion of the analyzers and other instrumentation along with the test and calibration procedures are outlined in GTI's report titled "SAMPLING AND ANALYTICAL QA/QC SUMMARY" presented in the appendix of this report. The Ecom analyzer, used for the long term testing, was originally set up so that it collected sample data for a 30 minute time period and then it was off for 6 minutes where it went through a purge and reset cycle. This 6 minute off time was later increased to 30 minutes to extend the lifetime of the sample pump. The original plan for calibration frequency of the Ecom analyzer was on a monthly basis but as data was collected it was recognized that this needed to be increased to twice a month. The data

acquisition continuously records data every five seconds but can be increased in frequency to every two seconds.

A new gas flow meter was installed February 17, 2009 because the original flow meter was drifting. The new flow meter was a Sierra Instruments model 640S steel mass industrial insertion thermal mass flow meter. The Sierra flow meter came from the factory calibrated. All the instrumentation was provided with an analog output signal that fed the information to the data acquisition.

Emissions performance from the boiler while carrying plant load has shown promising results. The averaged emissions data plotted at different points from February 26 and 27 was averaged at points where the gas flow remained constant for at least one minute at different firing rates through the boiler's firing range. The purpose of the averaged data at a constant firing rate was to give some time for the analyzer to stabilize. The results are shown in Figure 19. This figure also shows the corrected NO_x collected continuously for a 27.9 hour time period. It should be noted that the data collected while the boiler was modulating does not take into account the lag time between firing rate and when emissions were recorded from the analyzer. The data points are recorded at five second intervals. The average and standard deviation for all the continuous data recorded during this 27.9 hour time period was 4.0 ppmv and 0.9 ppmv, respectively. The analyzer used to record this data required six minutes of purge time for every 30 minutes of measurement time. The data in the plot and the averaged and standard deviation calculations were done without the data collected during this purge time.

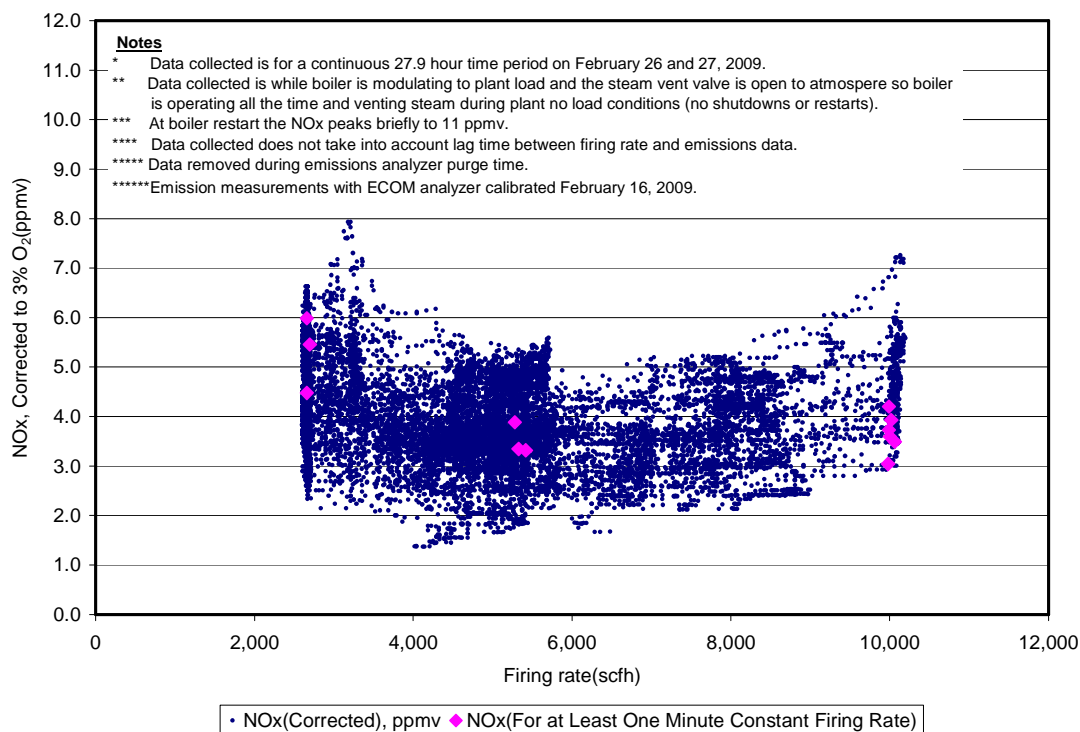


Figure 19. Averaged and Continuous Corrected NO_x Emissions Data at Different Firing Rates, February 27, 2009

Instantaneous data collected on March 2, 2009 for NO_x and O₂ during a four hour period of carrying the plant load is shown in Figure 20 below. It should be noted that the emissions

collected from the analyzer's 6 minute purge is where emissions are zero. This only includes data during operation and excluding the analyzer's purge time.

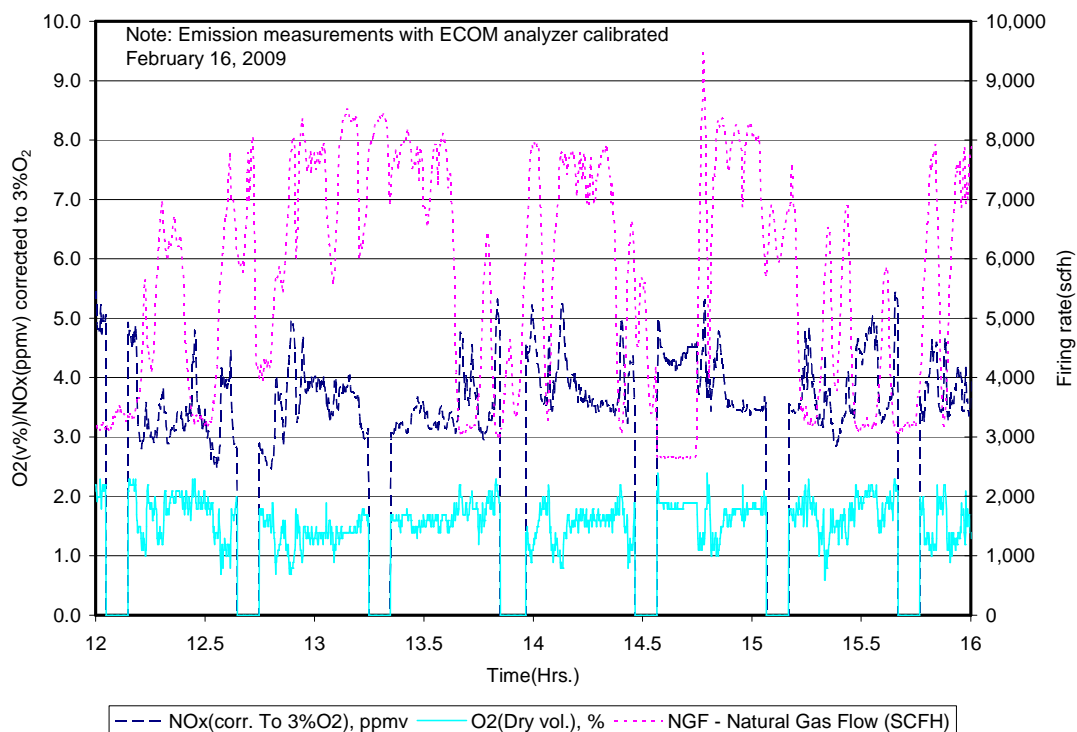


Figure 20. Running NOx and O2 Emissions During a Normal Plant Load Steam Vent Valve Open on March 2, 2009

A similar plot to Figure 20 is shown in Figure 21 for the CO emissions. This data shows that CO through the firing range was around 20 ppmv but there were occasional spike and one that went as high as 220 ppmv. The average CO emissions for this March 2, 2009 data starting at 12:00 noon for a 24 hour period was 19 ppmv. Again, this only includes data during regular operation while carrying plant load.

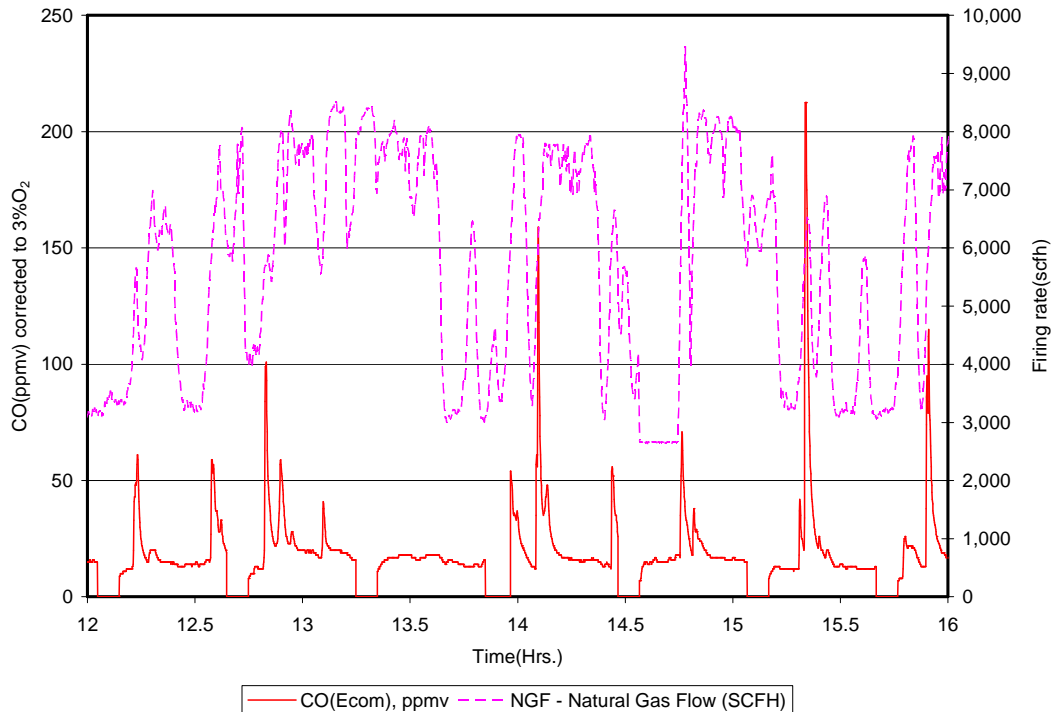


Figure 21. Running CO Emissions During a Normal Plant Load Steam Vent Valve Open on March 2, 2009

In the early afternoon on March 16, 2009 the steam vent valve was closed with the 600 HP in hot standby and the steam valve isolating it from the plant. This allowed the Super Boiler to cycle off during low demand times as well as modulate to varying steam load demand. Figure 22 shows the NO_x and O₂ emissions for a four hour time period under this condition. The 10 to 12 hour time period shows emissions during a process and then from 12 to 12.6 hour time period there is no steam demand. After the 12.6 hour time there is a steam load until just past the thirteenth hour. This is a cleaning process. After the thirteenth hour there is no demand from the process so that the boiler is only operating to keep the boiler and piping warm. This is the start of the four hour down time. During this time the Super Boiler is cycling on and off approximately every ten minutes.

The NO_x emissions during this cycling did spike occasionally, during the burner light off, up to 15 ppmv. The average corrected NO_x and measured O₂(dry) between 1:42 PM PST on March 16 to 9:29 AM PST on March 17, when the boiler and analyzer was operating, was 4.9 ppmv and 2.0%, respectively.

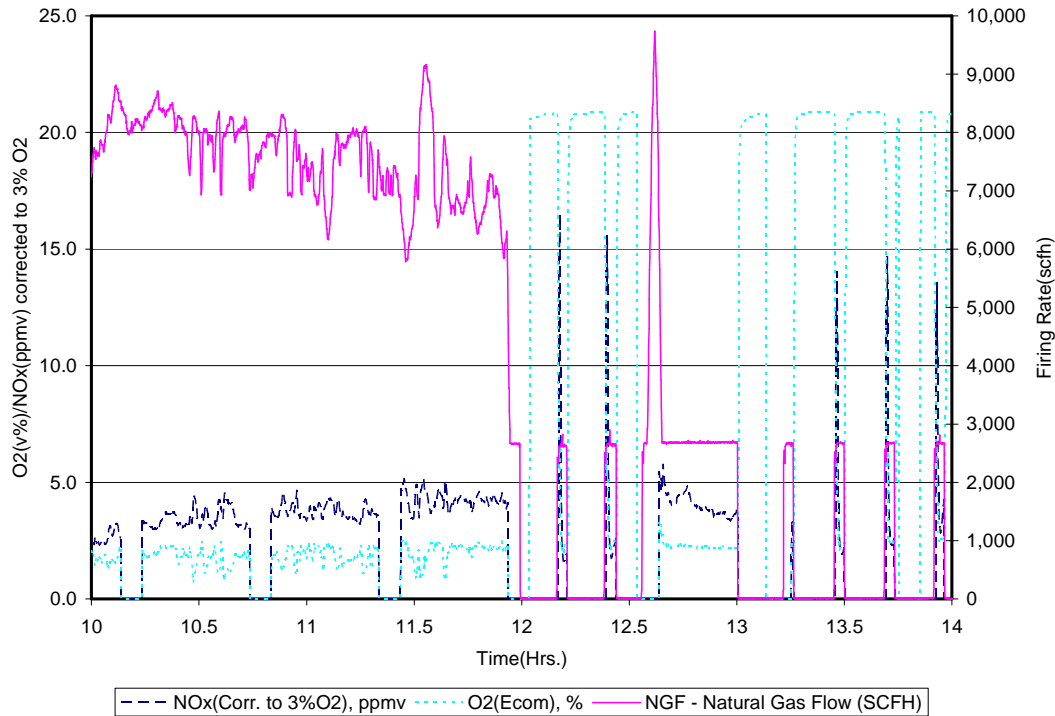


Figure 22. Running NOx and O2 Emissions During a Normal Plant Load Steam Vent Valve Closed on March 16, 2009

Figure 23 shows how the CO varies during the boiler cycling and modulation within the same time interval as Figure 22. The spikes in CO went beyond the analyzer range of 220 ppmv. These spikes take place during the light off and transition from single stage to two stage combustion. The averaged measured CO during this time period could not be calculated because of the spikes over 220 ppmv

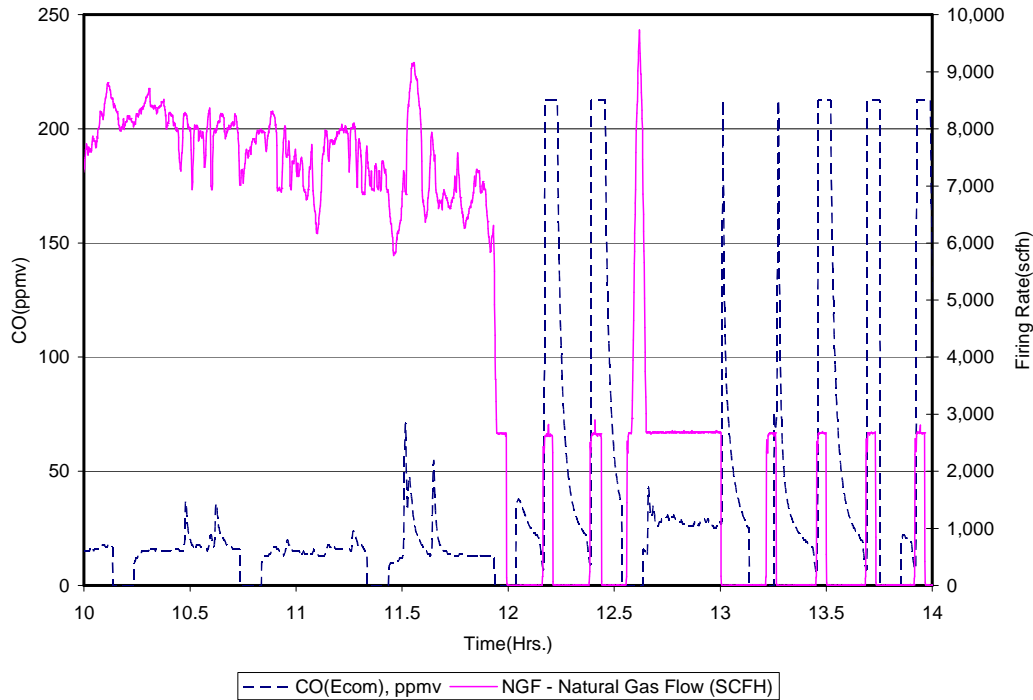


Figure 23. Running CO Emissions During a Normal Plant Load Steam Vent Valve Closed on March 16, 2009

Efficiency-Impact of cycling on the HRS

The efficiency of the Super Boiler with the HRS has been consistently operating around 92 to 93% despite low makeup water. One of the original requirements during the job site selection was to have a makeup water requirement greater than 25% for optimal TMC operation. This is important so the water temperature in the TMC stays cold enough so that the vapor will condense on the membrane tubes for transport through the membrane. The amount of makeup also impacts the amount of water going through the low pressure economizer (LPE) to the makeup tank. If makeup is low then the LPE cannot lower the flue gas temperature to an acceptable dew point before it goes into the TMC. The amount of makeup water has been around 12 to 15% since the steam vent valve has been closed.

The low makeup water also causes high water temperatures in the LPE which could cause damage it in the long term. One of the strategies implemented to reduce high water temperatures in the LPE was a bypass line was added from the outlet of the LPE to the inlet of the circulation pump for the HAH. This line had a control valve that was controlled by the outlet temperature of the LPE. The control valve would open and circulate water through the LPE to the HAH when the water temperature coming out of the LPE reached its set point. This scheme was first implemented at the first test site in Alabama. The bypass did not seem to work well at this site because there was 25% of the makeup water at CP compared to the Alabama site.

Another scheme implemented was to use the makeup tank as a holding tank to keep the makeup water flowing when the TMC outlet flue gas temperature reached a certain set point. This process would raise the normal makeup tank water level by two inches when the flue gas temperature from the TMC would go above 140°F and then four inches if the temperature would go above 145°F. This method worked at keeping the TMC water cool but once the makeup

tank's water level went above the normal level and the temperature of the flue gas from the TMC was below the set point temperature then there would be no flow through the LPE. This raised the flue gas temperature coming from the LPE farther from the dew point so the water in the flue gas was not condensing on the membrane tubes. This was the last change made to address this problem. It still needs to be addressed and will probably need some major rework to get it solved.

Figure 24 is a plot that shows the TMC flue gas inlet and outlet temperature. This demonstrates that the LPE is not lowering the flue gas temperature close enough to the dew point temperature needed, approximately 135°F, to condense the water in the flue gas. Also in this plot is the percentage of water transferred through the TMC membrane to the makeup water. There is no transfer made until the TMC inlet flue gas temperature gets to approximately 190°F. For instance, at 190°F inlet temperature with a temperature differential across the TMC of approximately 55°F then the flue gas can reach a flue gas temperature of approximately 135°F.

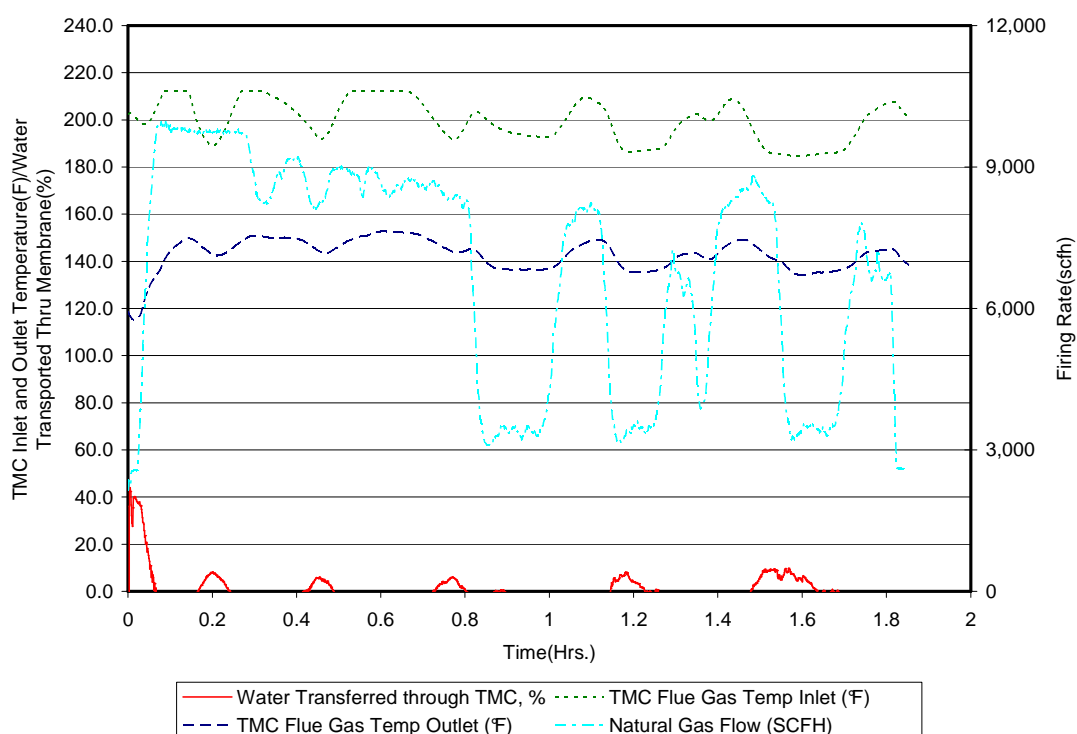


Figure 24. Running TMC Inlet and Outlet Flue Gas Temperature, Water Transferred Through TMC Membrane, and Firing Rate, April 16, 2009

Figure 25 is a plot of the dew point temperatures for the inlet and outlet of the TMC for the same time interval as Figure 24. This plot shows there are times when the outlet dew point temperature actually exceeds the inlet temperature. This may be partially due to inaccuracy of the dew point temperature probes.

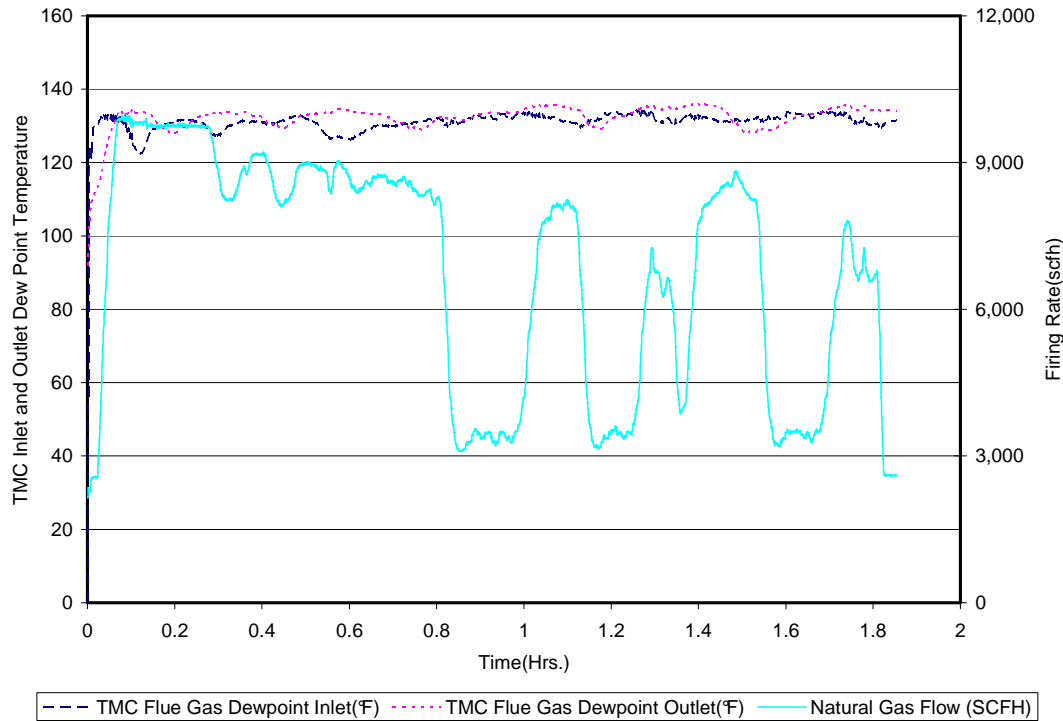


Figure 25. Running TMC Inlet and Outlet Flue Gas Dew Point Temperature, Firing Rate, April 16, 2009

Figure 26 is the fuel to steam conversion²⁴ and combustion efficiency²⁵ as a function of time during the plant processes. This plot is within the same time interval as Figure 24 and Figure 25. The combustion efficiency fluctuates between 91.8 to 94.8% with an average of 93.0%. The plot shows fluctuations in the efficiencies. These fluctuations can be partially explained by the variation in the transport of flue gas moisture through the membrane. The efficiency increases slightly when there is more water absorbed by the TMC because it is getting the benefit of the latent heat. There are also fluctuations because of the variation in the boiler's firing rate. The fluctuations are more pronounced in the fuel to steam conversion data. This plot varies from 40.9 to 100% with an average of 90.8%. This is largely due to the lag in response of the natural gas flow rate to the steam flow rate.

²⁴ Fuel-to-steam conversion is defined as $(Q_{\text{steam}})/(Q_{\text{fuel}}) \times 100$ where Q represents the heat values for the different components.

²⁵ Combustion Efficiency based on Stack Losses is defined as $100 - L_{\text{fluegas}} + L_{\text{TMC}}$ where L represents the heat loss values.

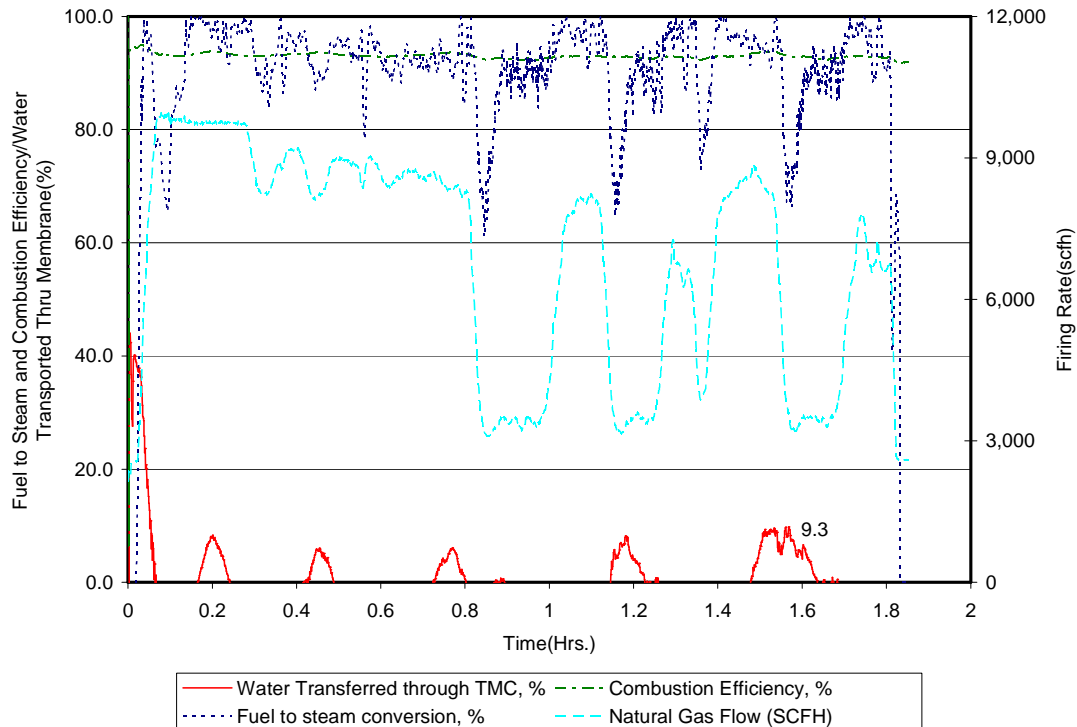


Figure 26. Running Fuel to Steam Conversion and Combustion Efficiency, Water Transfer Thru TMC, Firing Rate, April 16, 2009

Conclusions

Super Boiler technology can potentially replace 1148 existing firetube boilers in the AQMD territory, not counting new installations. An eight-year phase-in plan that also takes into account new facilities or facility expansions in the AQMD region forecasts installation of 176 boilers or heat recovery retrofits by 2020. Total fuel savings are projected to reach \$10 million by 2020.

The potential emissions reduction for the Super Boiler if we assume replacement of all South Coast AQMD boilers over 20 years old will result in annual emissions of 59 tons of NO_x and 142 tons of CO, which translates to avoidance of 49 tons of NO_x and 515 tons of CO. These reductions are the result of both efficiency increase and specific emissions.

Water savings also result from use of the Super Boiler because the TMC extracts water vapor from flue gas to displace boiler make-up water. Based on a typical water vapor content of 0.099 lb H₂O per scf of natural gas fired, previously estimated fuel usage data for 100-1000 hp AQMD boilers older than 20 years, and typical recovery rates for industrial and commercial boilers, replacing all these boilers in AQMD with Super Boilers could recover 47.3 million gallons per year (145 acre-ft per year) of clean water equivalent in purity to RO water. However, this is impractical since only 10-20% of all boilers in this area have sufficient makeup water available to recover the aforementioned water savings. Hence, if 15% of all 100-1000 hp firetube boilers older than 20 years were replaced with Super Boilers, 7.1 million gal per year (21.8 acre-ft per year) of clean water would be recovered.

The project team demonstrated the ability of the two-stage Super Boiler at Clement Pappas & Co. to deliver an average 92% fuel-to-steam conversion, 5 ppmv average NO_x, and 20 ppmv average CO emissions at stack oxygen in the range of 1.5 to 3.0 vol% (dry basis) which met the original goals while operating under steady conditions. Although there were occasional spikes of NO_x and CO during start up and such anomalies are forgiven during source testing.

There were several positive findings as a result of this project that are listed below:

- The two stage combustion system proved to be stable and reliable through the firing range.
- Initial operation of the Super Boiler has shown a 24% reduction in fuel usage.
- The heat recovery system worked well despite a low makeup water requirement of only 12 to 15%.
- The PLC controls for the burner worked well but may require further development depending on findings from the long term testing.
- The Super Boiler followed the site's steam load and was able to meet quick steam load demands.
- New technology requires extensive work with the customer in order for them to get comfortable with the equipment.
- The changes made in the reliability of the pilot made the ignition more reliable but further modifications may need to be made depending on the results from the long term testing.
- The HRS has handled the large and relatively short steam loads and extensive on and off cycling well but more long time monitoring will be needed.
- The low makeup requirements caused more reliance on the HAH to dissipate heat from the TMC which caused problems with water leakage.

Major control parameters that affect the ability of the boiler to maintain conditions within the desired optimal range were extensively studied and tuning methods for automatic control were implemented. Additional development to hold NO_x emissions below 5 ppmv during startup, shutdown, and firing rate transitions needs to be addressed as well as excursions detailed above.

Status of the Technology

The status of the Super Boiler technology is described in terms of the status of the two components of the Super Boiler: i.e., the two stage firetube boiler and the TMC heat recovery system.

Boiler component:

The boiler is of firetube design but unlike a conventional firetube boiler with one combustion chamber, the Super Boiler has two separate combustion chambers with interstage cooling section between the two combustion chambers (Patent # 6,971,336 B1, Dec. 2005), thus the term two stage firetube boiler. These two separate combustion chambers provide for the two stage combustion system of fuel rich (1/6 air to fuel ratio) combustion in the primary zone and a secondary combustion zone where the remaining combustion air is provided to complete the combustion (Patent # 6,289,851, Sept. 2001). The firetube design is also a two pass design, i.e. the first pass is the combustion sections and the second pass is the convective section where multiple small convective tubes are employed. The Super Boiler employs Cleaver Brooks "AluFer" (aluminum fins) inserts into a portion of the convective tube length to extract additional heat from the flue gases in the convective section of the boiler. The Super Boiler also uses a rear water cooled door to eliminate refractory in the back of the boiler and this rear door provides for complete access to the secondary combustion chamber and the turning section from the first to the second pass of the boiler.

The first boiler of the Super Boiler two stage firetube design was a laboratory 75 HP 150 psig steam design (3 MMBtu/hr firing rate) unit and was tested from July 2004 to July 2005 at GTI as part of a DOE development (DE-FC36-00ID13904) of the two stage combustion system. The burner was of gun style with external combustion air fan. This laboratory experimental boiler was fired as high as 5 MMBtu/hr natural gas flow and achieved less than 5 ppm NO_x and less than 10 ppm CO over the range of 1 to 5 MMBtu/hr input with oxygen in the flue gas in the range of 1 to 3 % at steady state conditions.

A 300 HP 150 psig steam design of a two pass firetube boiler (conventional single combustion chamber) with alufer tube inserts in convective pass tubes and the rear water cooled door was first tested as part of the DOE demonstration program of the TMC heat recovery system in Alabama (at Specification Rubber) beginning in 2005 and is still operating today. It confirmed the successful application of the alufer tubes to provide a compact boiler footprint for the 300 HP size with boiler flue gas temperature of 50 F above saturated steam temperature and successful operation of the rear water cooled door. Subsequently, the AluFer tubes have been applied by Cleaver Brooks to over 20 two pass "Ohio Special Boilers".

The 300 HP 150 steam design of the Super Boiler was designed and fabricated in 2006, and tested as part of the development of the two stage combustion system for this size boiler including the combustion control system at the Cleaver Brooks Thomasville, GA plant from the fall of 2006 to the spring of 2007. It should be noted that the primary zone burner on the 300 HP Super Boiler is applied as part of the Cleaver Brooks standard integral front head design of the boiler which includes the combustion air fan in the integral head. The Super Boiler for the Clement Pappas facility was permitted for less than 9 ppm. Installation was completed in the fall of 2007 at Clement Pappas, Ontario, California. Initial startup of the boiler followed shortly in 2007.

After 6 months of successful on line operation (scheduled for Sept. 2009) of the Super Boiler carrying the steam load of the Clement Pappas facility, GTI's partner Cleaver Brooks is scheduled to make a decision on the licensing of the technology. Based on other successful new products in the boiler area, a new boiler product line for the Super Boiler would be likely,

which involves Super Boilers from 100 HP to 1000 HP in size. The scale up factors would be verified by fabricating one or two sizes (i.e. 600 HP and 1000 HP) and fully testing the two stage combustion systems before the complete fabrication drawings for the entire product line are prepared. It should also be noted that the Super Boiler is presently limited to 150 psig design because of the AluFer tube insert temperature limitation.

Additional testing is required on the two stage burner in order to optimize the reliability, stability and safety. In particular, additional work must be done on the pilot to achieve consistent lightoffs. At this time the boiler is experiencing approximately 95% successful lightoffs, but >98% is required to meet customer expectations. In addition, work must be done to improve turndown of the burner such that it meets that of existing product offerings. Finally, the burner and it's emissions must be monitored long term (over 12 months) to document any emission or performance changes that occur over time, as the result of worn gaskets, linkages and other mechanical devices.

Long term maintenance of the two stage burner and boiler is unknown since the Clement Pappas unit is the first beta site. Demand is strong for a boiler that does not use refractory because refractory requires maintenance and in addition, data has revealed that hot refractory can cause unplanned lightoffs. The existing two stage burner employs refractory in both the primary and secondary zone burners. For a safer, more maintenance free boiler, the burner elements would be preferred to be changed to all metal construction. This would involve testing with a Thermal Barrier Coating (TBC) similar to what is used on the internal recirculation sleeve on the primary zone burner of the Super Boiler to cover the metal surfaces to protect the metal parts and provide a hot surface exposed to the flame.

Development of the Super Boiler product line is estimated to take up to 36 months. During the interim period, it would be beneficial if 2 to 5 additional 300 HP 150 psig design Super Boiler units are installed under some customer subsidy program (Federal, state, or other) to expedite the general acceptance of the Super Boiler Technology.

TMC Heat Recovery System

The TMC Heat Recovery System is based on GTI (Patent # 6,517,607) Transport Membrane Condenser (TMC), which recovers both sensible and latent heat from flue gases to achieve energy efficiency up to 94 % (HHV). The TMC recovers a portion of the sensible heat in addition to recovering up to about 50% of the flue gas water vapor from boiler flue gases which then can be reused in the system.

The TMC Heat Recovery System was first tested in the GTI laboratory as part of the DOE Development program (DE-FC36-00ID13904) on the Super Boiler. The first demonstration of the technology was in Alabama at Specification Rubber in early 2005 on the 300 HP boiler application. The TMC heat recovery system at Specification Rubber consisted of the first generation TMC, and two economizers, one a conventional high pressure economizer (HPE) that uses the boiler flue gas to preheat the hot water from the Deaerator to the boiler and a second low pressure economizer (LPE) that also use the flue gas from the HPE to heat the warm makeup water that exits the TMC and goes to the Deaerator. The TMC heat recovery system also has a humidifying air heater (HAH) to preheat combustion air with the warm water that is recirculated from the TMC to the HAH and back to the TMC to increase the heat recovery in the TMC by increasing the water flow rate through the TMC. The Specification Rubber application is a 50 % makeup water condition. The boiler typically fired at 40 to 50 % capacity and achieved 94 % plus efficiency. For this application of the TMC, 35 % of the water vapor in the flue gas was captured by the TMC and brought back to the boiler and thereby decreasing the makeup water to the boiler by 6%. During the early period of the 3 year field testing at Specification Rubber, the TMC was accidentally exposed to untreated well water for about two

weeks which completely coated the ceramic tubular membranes of the TMC with rust. After 6 months of operation the TMC was inspected and nanoporous ceramic tubular membrane modules removed and the transport water flow rate measured for individual TMC modules. Despite the covering of rust the TMC module transport water flow rate was the same as originally installed.

The 300 HP Super Boiler at Clement Pappas in Ontario, California, has also the first generation of the TMC heat recovery system and is the 2nd installation of the TMC heat recovery system. Unlike the Specification Rubber, Alabama site, the Clement Pappas site under normal operating conditions has a high condensate return and therefore has only between 10 to 15 % makeup water requirement. The CARB ICAT project allowed GTI and its partner Cleaver Brooks to monitor and record the operation and performance of the TMC Heat Recovery system under the low water make conditions. The complete evaluation of this data will need additional long term testing to determine the water recovered from the flue gas and accordingly the reduction in makeup water for the Clement Pappas operations. As mentioned the Clement Pappas site reports a fuel savings of 24 % based on 2 ½ months of the Super Boiler carrying the steam load of the plant. These fuel savings are primarily due to the TMC Heat Recovery System. It is estimated that the 24 % fuel savings is equivalent to a 92 % efficiency boiler for the Super Boiler to a 74 % efficiency boiler for the Clement Pappas existing 600 HP firetube boiler.

A 2nd generation TMC heat recovery system employs “drawer type” TMC modules that allows for easy access for maintenance. These TMC modules employ seal potting of the ceramic membrane tubes to a set of tubesheets. In the original design, flue gases flow in the membrane tubes and make up water was on the outside of the membrane tubes, in the 2nd generation design the make up water flows in the tubes and flue gases flow upward on the outside of the tubes. This is a more effective design that has reduced number of ceramic membrane tubes and therefore more economical to produce. A standard 33 HP TMC module is presently being utilized on a number of additional Super Boiler applications. The TMC housing for the 2nd generation design also includes an integrated compact low pressure economizer which allows the TMC/LPE to be positioned directly above the HPE to reduce the installation cost. The 2nd generation TMC heat recovery system with prototype TMC modules was successfully tested at Cleaver Brooks R&D in the summer of 2008. Material issues of the thermoplastic tubesheet and sealants employed in the 2nd generation TMC prototype surfaced after testing resumed 3 months later. These material issues have been resolved with thermoset tubesheet material and epoxy sealant that has survived extreme hot testing of 235 F simulated flue gases with little to no water flow rate in the tubes.

Five demonstration 2nd generation TMC heat recovery applications are underway and are planned to be up and running by the end of 2009 or early 2010. These include TMC heat recovery retrofits to one existing 250 HP and one existing 350 HP boiler and three TMC heat recovery systems on new 300 HP boilers. The applications include make up water flow rates from 100% down to 10%.

For the low make water flow rates a compact air heater has replaced the humidifying air heater in the TMC heat recovery system to preheat the combustion air and allow for increase flow rate of recirculated make up water flow to the TMC. The TMC heat recovery system with the air heater reduces the control and further reduces overall system cost. The control system for the heat recovery is integrated into the boiler control panel for new boilers and is a separate controller for retrofit systems.

These five 2nd generation TMC heat recovery applications will provide data for a variety of installation conditions, makeup water rates, makeup water temperature, and various specific site conditions. This type of information is required before this technology can be commercialized

because our commercial partners cannot currently accept the risk associated with an untested 2nd generation design, nor can they accept the risk associated with the initial 1st generation design. Hence it is envisioned that after all five 2nd generation TMC heat recovery applications are successfully operational for at least 12 months, our commercial partner will be willing to take this product to the market.

In the interim, work is underway to reduce costs of the components. In addition, a program to integrate the TMC, LPE and HPE into a single package will soon commence which would greatly reduce installation cost.

Relationship to Regulatory Structure

The Super Boiler is designed to be a cost-effective, energy-efficient method to meet current and future NOx regulations for steam and hot water boilers. Depending on the location of the boiler (attainment/ non-attainment area) and the nature of the installation (new/ replacement), the boiler may have to comply with RACT, BACT, or LAER abatement measures. These measures differ among the 35 local Air Districts, but all must comply with ARB and Federal rules.

In the past year, a few regulatory agencies have implemented NOx levels that cannot be met by existing burners, and therefore add on technologies such as selective catalyst reduction (SCR) have been used which substantially increase system cost. The Super Boiler will offer an attractive alternative in these cases, and consequently will help encourage business growth with very minimal impact on air quality.

Market Analysis

Target markets are commercial, institutional, and industrial facilities that use steam or hot water. In particular, industries that make heavy use of steam and for which steam generation is a large component of their energy use constitute the most attractive markets. Specific types of facilities that would be targeted include:

- Food and beverage processing plants
- Paper products manufacturers
- Specialty chemical manufacturers
- Metals processors (integrated steel making, aluminum smelting, blast furnace/iron making)
- Pharmaceutical manufactures
- Universities
- Primary and secondary schools
- Hospitals
- Airports
- Correctional facilities
- Large hotels
- Military bases

The main incentive for customers in these industries to purchase Super Boiler technology is to save money on fuel usage while simultaneously ensuring compliance with current and anticipated future emissions regulations. Because the technology is considered "cutting-edge" and may be unfamiliar to conservative facility managers, numerous successful demonstrations

are essential to move beyond the "early adopters" or customers that are positioned to take advantage of subsidized programs. The money-saving energy efficiency benefits of the Super Boiler also ensure that customers outside of severe non-attainment areas will also find the technology economically attractive.

The targeted industries are mainly stable established sectors whose growth will parallel general economic growth. Steam/hot water generation is considered a "cross-cutting" technology that is of greatest interest to energy-intensive industries such as pulp and paper, chemicals, and food processing.

Competition

Competitors to the gas-fired Super Boiler include conventional gas-fired boilers that use ultra-low-NO_x (ULN) combustion systems, downstream emission controls such as selective catalytic reduction (SCR), and electric boilers. Unlike the Super Boiler, ULN combustion systems do not improve efficiency, but in nearly every case actually *degrade* energy efficiency. This is because ULN combustion technologies use either:

- Flue gas recirculation (FGR) that increases the electric load on the blower and also increases the volume of flue gas and consequent stack loss, or
- High excess air that results in significantly higher stack losses, or
- Steam injection that consumes a portion of the product steam to reduce NO_x, or
- Water injection that increases the heat load required to evaporate water that ultimately goes up the stack with its latent heat, or
- SCR, considered state-of-the-art for deep NO_x reduction, requires the use of expensive chemical reducers such as ammonia or urea.

With regard to SCR, stack conditions also must be maintained within optimal ranges of flow and temperature, which imposes constraints on boiler operation and can result in ammonia slip if such optimal conditions are not maintained. SCR requires extensive ductwork modification and additional equipment that reduce system efficiency. The Super Boiler can achieve emissions reductions comparable to SCR while increasing system efficiency.

Super Boiler is expected to be only marginally higher (10%-20%) in capital cost than conventional boilers because the additional complexity of design and construction resulting from the two-stage combustion design is offset in part by lower material costs resulting from a boiler that is >30% smaller in size when compared to traditional boilers. The advanced heat recovery system is being value engineered and is expected to have a payback of < 2 years. Life-cycle costs are expected to be significantly lower than conventional boilers and much lower than competitive technologies because of the fuel savings.

The only true competition to the HRS is condensing economizers because they can recover both sensible and latent heat from the fuel gases, wherein most other heat recovery products only recover the sensible heat. Condensing economizers can be used to increase boiler efficiency up to 90% when makeup water rates are 100% (this compares to a HRS which would provide 95% efficiency with 100% makeup water rate) – they are typically 4-5% less efficient than a HRS.

Condensing economizers have several limitations including application to low makeup water conditions and corrosion. When makeup water rates are below 25%, only localized condensing occurs in a condensing economizer and in many cases this localized condensate is then re-evaporated, hence efficiency becomes equal to a non condensing economizer. The HRS system can be applied to makeup water rates down to 10% while still collecting latent heat.

Finally, condensing economizers do not recover and reuse humidity in the flue gas, instead they condense this water vapor and unfortunately that condensation is pH acidic due to small amounts of sulfur in the flue gas. Therefore condensing economizers must be made of stainless steel to reduce corrosion, and the collected condensate must be treated to a neutral pH before it is disposed of into the municipal drain.

Financial Projections

The capital requirement to bring the Super Boiler to market is currently being evaluated.. The public awareness of Super Boiler technology is strong in the United States due to excellent exposure from Federal, State and Local agencies as well as numerous trade organizations. However quantifiable demonstration sites are required to warrant full commercialization and reduce risk to commercialization partners. These partners require that a minimum of five (5) Super Boilers must be operational for at least one year each in order to warrant full commercialization expenditure of such magnitude. GTI is committed to having at least five TMC Heat Recovery System components of the Super Boiler technology operational by the end of 2009.

Funding will be provided internally by the commercialization partner, Cleaver-Brooks, from its normal operating profit, similarly to its funding for the introduction of any new boiler product. Cleaver-Brooks is a privately owned U.S. corporation. In addition, we have completed serious discussions with additional commercialization partners in the event that Cleaver-Brooks decides not to take the product to market.

Preliminary pro-forma income projections, three-year projections, and break-even analysis for the Super Boiler have been determined but their publication would not be prudent until the qualification of five systems has been accomplished and that cost data is made available.

Key Players

The key player in commercialization of the Super Boiler is the manufacturing partner, Cleaver-Brooks, which has a worldwide network of over 1500 sales representatives. The Super Boiler will be manufactured under licensing terms which have commenced between GTI and Cleaver-Brooks. It should be noted that at this time, Cleaver-Brooks will not manufacture any additional two stage boilers because there is insufficient data on long term emission levels, reliability and safety. It is expected that the heat recovery technology, particularly the TM condenser, will be available for license to other manufacturers for applications other than steam generation (e.g., heat recovery from drying operations).

Appendices

